GEORGIA DEPARTMENT OF NATURAL RESOURCES
ENVIRONMENTAL PROTECTION DIVISION

Lakes Burton, Rabun, and Tugalo Proposed Criteria

Technical Support Document

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1.0 INTRODUCTION

Lakes Burton, Rabun, and Tugalo lie in the Savannah River watershed in north Georgia, approximately 90 miles northeast of the city of Atlanta (Figure 1-1). Lake Burton is a 2,775 acres (11.23 km^2) reservoir with 62 miles (100 km) of shoreline located in the northeastern corner of Georgia in Rabun County in the Blue Ridge Mountains. The lake is owned and operated by the Georgia Power/Southern Company, but it is a public lake. Lake Burton was constructed in a deep valley along a 10-mile (16 km) section of the Tallulah River. Its dam was completed on December 22, 1919, and the lake was declared full on August 18, 1920. The dam is a gravity concrete dam, with a height of 128 feet (39 m) and a span of 1,100 feet (340 m). The spillway is equipped with eight gates 22 feet (6.7 m) wide by 6.6 feet (2.0 m) high. The total capacity at the full pool elevation of 1,866.6 feet (568.9 m) is 108,000 acre·feet (133,000,000 m^3), of which 106,000 acre·feet (131,000,000 m^3) is usable storage. The maximal depth of the lake is 105 feet at the dam pool. The generating capacity of the dam is 6,120 kilowatts (two units). Lake Burton is the highest Georgia Power lake in Georgia.

Lake Rabun is an 835-acre (3.4 km^2) reservoir with 25 miles (40 km) of shoreline also located in Rabun County. It is the third lake in a six-lake series that follows the original course of the Tallulah River. The property was originally purchased by the Georgia Railway and Power Company later renamed Georgia Power Company. Lake Rabun's Mathis Dam was completed in May 1915, but the lake was not filled for ten years waiting for the completion of a tunnel from near the dam to the power generator at Tallulah Falls. The Mathis Dam is an ambursen-type concrete dam with a height of 108 feet (33 m) and a span of 660 feet (201 m). The reservoir is over ten million gallons covering 834 acres (3.4 km^2) and full pool elevation is at 1,689.6 feet (515.0 m). The Terrora Hydroelectric Plant at Mathis Dam has a generation capacity of 16,000 kilowatts.

Lake Tugalo is a 597-acre (2.42 km^2) reservoir with 18 miles (29 km) of shoreline located in the northeastern Georgia in Habersham and Rabun counties, and also lies partially in Oconee County, South Carolina. It is the fifth lake in a six-lake series created by hydroelectric dams operated by Georgia Power that follows the original course of the Tallulah River. The series starts upstream on the Tallulah River with Lake Burton followed by Lake Seed, Lake Rabun, Lake Tallulah Falls, and Lake Tugalo. Lake Tugalo began filling in 1923 with the completion of the Tugalo Dam, a gravity concrete and masonry dam. The dam is 155 feet (47 m) high and has a span of 740 feet (230 m). Full pool is at an elevation of 891.5 feet (271.7 m). The Tugalo Hydroelectric Plant has a generation capacity of 45 megawatts. All three lakes generate hydroelectric energy for Atlanta, which is 90 miles to the southwest. At one time these lakes were the largest producers of electricity in the state. Now, they only provide peak power.

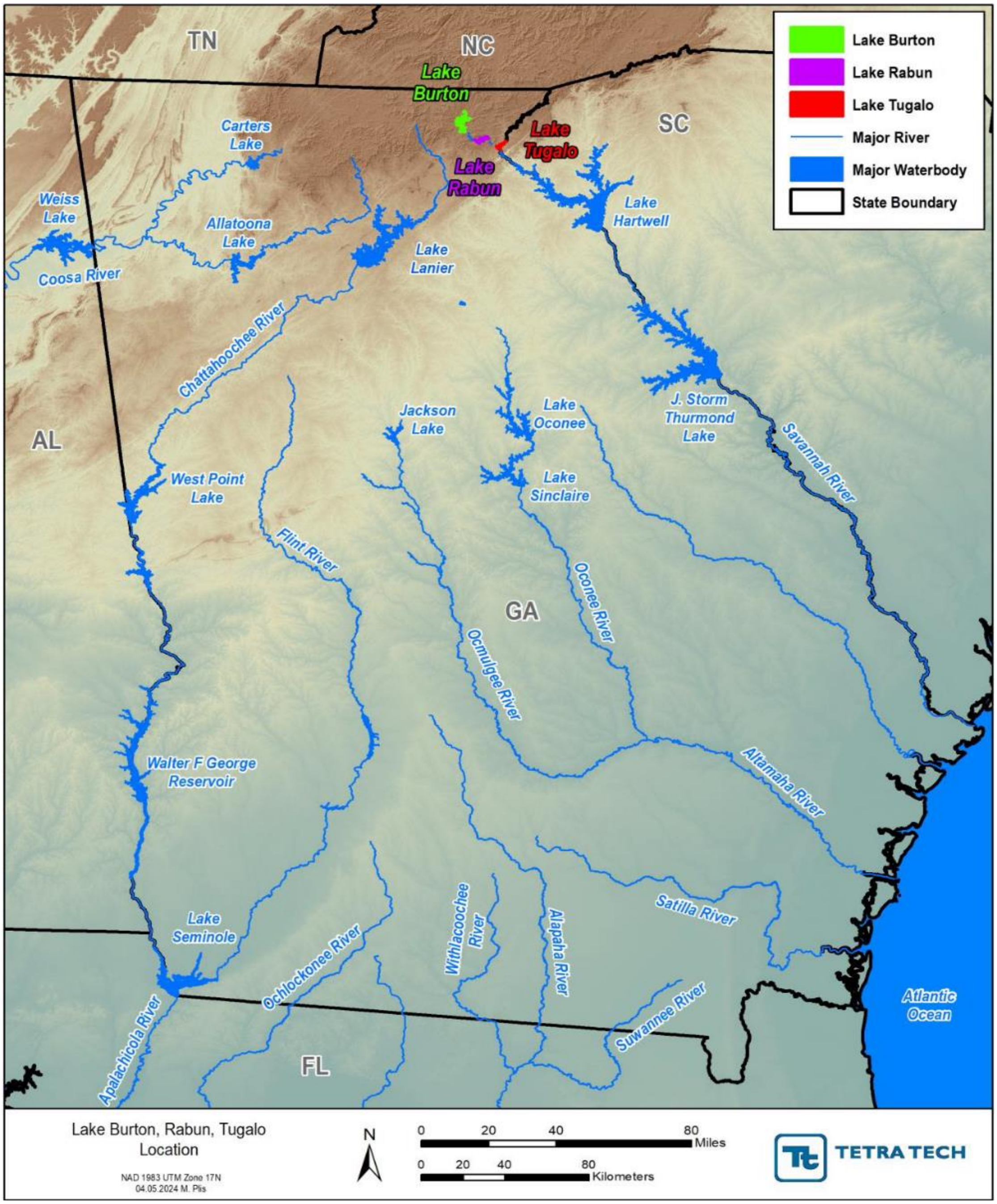

Figure 1-1. Location Of Lakes Burton, Rabun, and Tugalo In Georgia

Figure 1-2 shows the drainage area of each lake. The drainage area of Lake Burton is 117.3 square miles, Lake Rabun's drainage area is 35.5 square miles plus that of Lake Burton's, and the drainage area of Lake Tugalo is 315.6 square miles, plus that of Lake Burton and Rabun. Land cover in the lake drainage areas is predominantly forested (see Figure 1-3). However, there are some residential and commercial areas in the Lake Tugalo watershed near Clayton, Georgia.

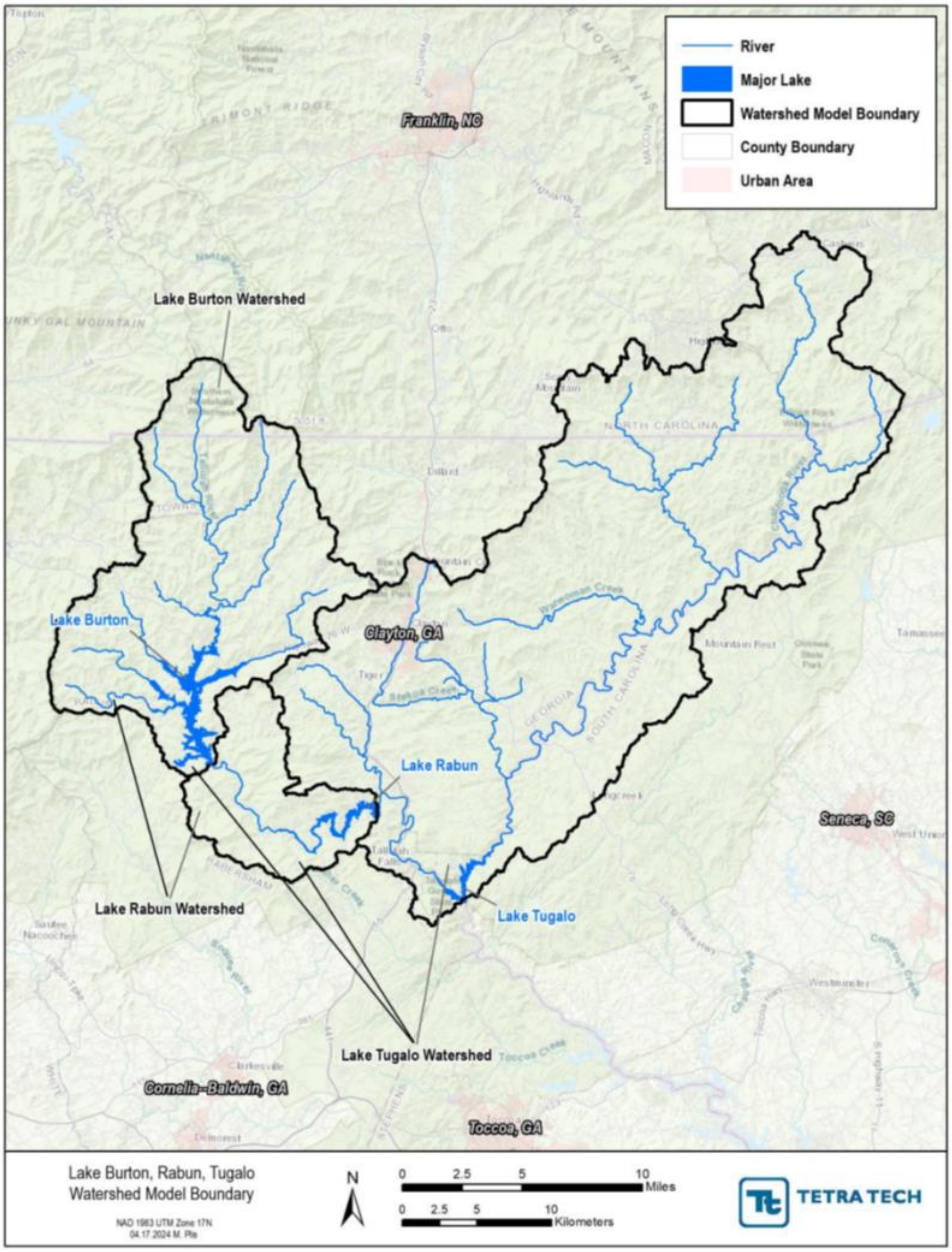

Figure 1-2. Lakes Burton, Rabun, and Tugalo Watersheds

Table 1-1 presents a breakdown of the land cover for each lake watershed provided in the 2008 Georgia Land Use Trend (GLUT) land cover dataset (Figure 1-3). The Table presents the acreage and percentage of each land cover.

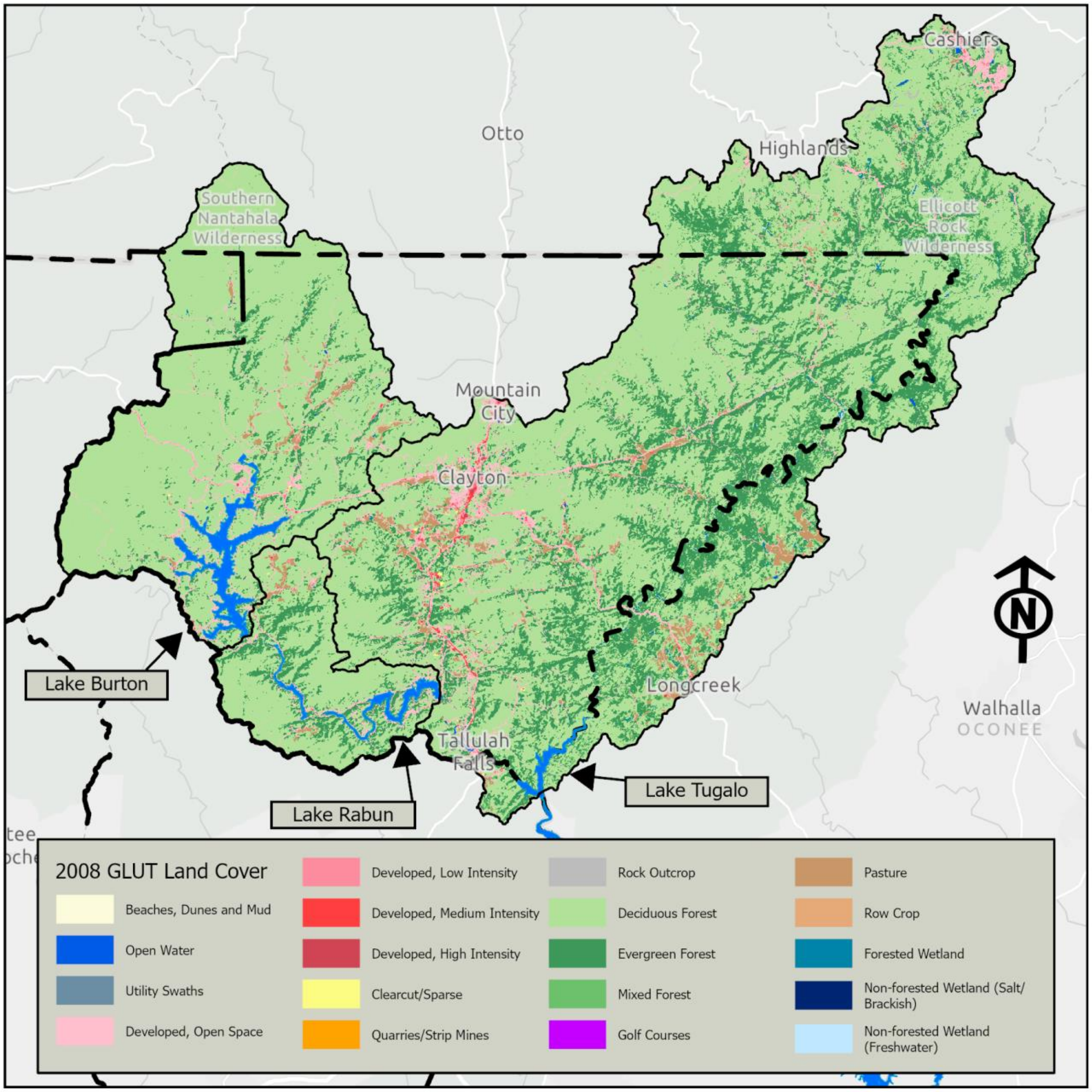

Figure 1-3. Land Cover For Lakes Burton, Rabun, and Tugalo Watersheds From 2008 GLUT

Table 1-1. Amount and Percentages of Land Cover from 2008 GLUT Dataset

Land Cover Category	Lake Burton		Lake Rabun		Lake Tugalo	
	Acres	%	Acres	%	Acres	%
Beaches, Dunes, Mud	1.6	0.0%	0.7	0.0%	1.3	0.0%
Open Water	2,429.9	3.2%	813.3	3.6%	892.9	0.4%
Utility Swaths	0.0	0.0%	0.0	0.0%	13.3	0.0%
Developed, Open Space	3,322.6	4.4%	1,319.5	5.8%	10,372.3	5.1%
Developed, Low Intensity	227.7	0.3%	56.9	0.3%	1259.9	0.6%
Developed, Medium Intensity	37.8	0.1%	11.1	0.0%	532.0	0.3%
Developed, High Intensity	2.9	0.0%	0.4	0.0%	101.6	0.1%
Transitional, Clearcut, Sparse	24.5	0.0%	12.2	0.1%	227.1	0.1%
Quarries, Strip Mines	0.0	0.0%	0.0	0.0%	0.9	0.0%
Rock Outcrop	27.1	0.0%	0.0	0.0%	126.5	0.1%
Deciduous Forest	63,012.0	83.9%	15,789.8	69.4%	128,982.3	63.8%
Evergreen Forest	4,655.8	6.2%	4,069.6	17.9%	47,850.7	23.7%
Mixed Forest	316.9	0.4%	218.8	1.0%	6,226.2	3.1%
Golf Courses	0.0	0.0%	0.0	0.0%	0.0	0.0%
Pasture, Hay	954.3	1.3%	440.3	1.9%	4919.8	2.4%
Row Crops	32.0	0.0%	0.0	0.0%	71.2	0.0%
Forested Wetlands	42.7	0.1%	9.3	0.0%	433.7	0.2%
Non-Forested Wetlands (Salt/Brackish)	0.0	0.0%	0.0	0.0%	0.0	0.0%
Non-Forested Wetlands (Freshwater)	2.2	0.0%	0.4	0.0%	42.0	0.0%
Total	75,090.1	100%	22,742.5	100%	202,053.7	100%

Rabun County utilizes Lake Rabun as the raw water source for a portion of their drinking water needs. The Rabun County Water & Sewer Authority formerly known as the Clayton-Rabun County Water & Sewer Authority has a permit from GA EPD's Surface Water Withdrawal Program (119-0101-03) to withdrawal a total of 3.5 million gallons per day (MGD); 2 MGD from Lake Rabun in the Savannah River Basin and 1.5 MGD from the Little Tennessee River in the Tennessee River Basin.

There is one permitted point source in the Lake Burton watershed, one permitted point source in the Lake Rabun watershed, and four permitted and one proposed point sources in the Lake Tugalo watershed. Of the six dischargers in Lakes Burton, Rabun, and Tugalo, only three facilities currently have total phosphorus (Total P) permit limits. The other three facilities currently have total phosphorus monitoring requirements. Table 1-2 presents the summary of current and proposed point source discharges to Lakes Burton, Rabun, and Tugalo watersheds.

Table 1-2. Summary of Point Source Discharges to Lakes Burton, Rabun, and Tugalo Watersheds

Permit Number	Facility Name	Nearest Downstream Lake	Receiving Water	Permitted Flow (MGD)	Permitted Phosphorus Limit (mg/L)
Lake Burton Watershed					
GA0029840	Lake Burton Hatchery	Lake Burton	Lake Burton	Report	Monitor
Lake Rabun Watershed					
GAG550102	Christian Spiritual Alliance Inc. DBA Center for Spiritual Awareness	Lake Rabun	Unnamed Tributary to Lake Rabun	0.004	5.0
Lake Tugalo Watershed					
GAG550128	Athens Y Camp Chattooga (Athens Y Camp Chattooga WPCP)	Tallulah Falls Lake	Unnamed Tributary to Tallulah River	0.0042	5.0
GAG550004	Athens Y Camp For Boys (Athens Y Camp for Boys WPCP)	Tallulah Falls Lake	Unnamed Tributary to Tallulah River	0.0105	5.0
TBD [A]	Rabun County Water & Sewer Authority (South Rabun WRF)	Tallulah Falls Lake	Tallulah River	0.4	0.5
GA0035441	Tallulah Falls School (Tallulah Falls School WPCP)	Tugalo Lake	Unnamed Tributary to Tallulah River	0.005[B]	Monitor
GA0020923	Rabun County Water & Sewer Authority (Stekoa Creek WRF)	Tugalo Lake	Stekoa Creek	1.0	Monitor
				2.0	1.0

A – Proposed facility issued wasteload allocation (WLA000088) in January 2020
B – Cold weather stream discharge (November – April) with LAS only during May through October

Many smaller communities use land application systems (LAS) for treatment and disposal of their sanitary wastewater. The LAS permits require these facilities to treat all their wastewater by land application and properly operate the LAS as non-discharging systems that contribute no runoff to nearby surface waters. However, runoff during storm events may carry surface residual that contains nutrients to nearby surface waters. Some of these facilities could exceed the ground percolation rate when applying the wastewater, resulting in surface runoff from the field. If not properly bermed, this runoff, which probably contains nutrients, may be discharged to nearby surface waters. Table 1-3 provides a list of the LAS in the Lakes Burton, Rabun, and Tugalo watersheds.

Table 1-3. Summary of Land Application Systems in the Lakes Burton, Rabun, and Tugalo Watersheds

Permit Number	Facility name	Nearest Downstream Lake	Sprayfield Acres	Type	Permitted Flow (MGD)
GAJ030753	Ramah Darom Inc. (Camp Ramah Darom WPCP)	Lake Burton	3.0	Advanced septic and drip field	0.027
GAJ030794	Waterfall Property Owners Association (Waterfall at Lake Burton WRF)	Lake Burton	15.0	Reuse and spray field	0.075

The Georgia Rules require any person who is the owner of an Animal Feeding Operation (AFO) that is defined as a Concentrated Animal Feeding Operation (CAFO) per 40 CFR 122 and discharges to water of the State apply for a NPDES Permit. Or, if the Division has made a case-by-case designation as a CAFO, the owner of the CAFO must apply for an NPDES permit. Otherwise, any person who is the owner of an AFO with more than 300 animal units (AUs) and uses liquid manure handling must apply for an LAS permit from the Division. There are no permitted AFOs or CAFOs in the Upper Savannah watershed.

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2.0 PROPOSED LAKE CRITERIA

Lake Burton is the waters impounded by Lake Burton Dam and upstream, on the Tallulah River as well as other impounded tributaries to an elevation of 1866.6 ft mean sea level (MSL), corresponding to the normal pool elevation. Lake Burton has a volume of 108,000 acre-feet at full pool. Water quality standards have been proposed for this lake as part of the 2022 Triennial Review. Its designated uses are Recreation and Fishing. Lake Burton is currently meeting its designated uses. The proposed chlorophyll *a* criteria for the lake are as follows:

(i) Chlorophyll *a*: For the months of April through October, the average of monthly mid-channel photic zone composite samples shall not exceed the chlorophyll *a* concentrations at the locations listed below more than once in a five-year period:

1.	1/4 mile South of Burton Island (aka Tallulah River):	6 µg/L
2.	Dampool (aka Tallulah River - Upstream from Lake Burton Dam):	6 µg/L

Lake Rabun is the waters impounded by Mathis Dam and upstream, on the Tallulah River, as well as other impounded tributaries to an elevation of 1689.6 ft MSL, which corresponds to the normal pool elevation. Lake Rabun has a volume of 30.71 acre-feet at full pool. Water quality standards have been proposed for this lake as part of the 2022 Triennial Review. Its designated uses are Drinking Water, Recreation and Fishing. Lake Rabun is currently meeting its recreation and drinking water designated uses. Its fishing use is impaired for mercury and selenium based on fish consumption guideline recommendations and is assessment pending for low pH that may be due to low conductivity. The proposed chlorophyll *a* criteria criteria for the lake are as follows:

(i) Chlorophyll *a*: For the months of April through October, the average of monthly mid-channel photic zone composite samples shall not exceed the chlorophyll *a* concentration at the locations listed below more than once in a five-year period:

1.	Approx. 4.5 mi u/s Dam (Mid Lake):	6 µg/L
2.	Dampool (aka Tallulah River - Upstream from Mathis Dam):	6 µg/L

Lake Tugalo is the waters impounded by Tugalo Dam and upstream on the Tallulah and Chattooga Rivers to an elevation of 891.5 ft MSL, which corresponds to the normal pool elevation. Water quality standards have been proposed for this lake as part of the 2022 Triennial Review. Its designated uses are Recreation and Fishing. Lake Tugalo is currently meeting its designated uses. The proposed chlorophyll *a* criteria for the lake are as follows:

(i) Chlorophyll *a*: For the months of April through October, the average of monthly mid-channel photic zone composite samples shall not exceed the chlorophyll *a* concentrations at the locations listed below more than once in a five-year period:

1.	Upstream of Tugalo Lake Rd (aka Bull Sluice Rd.):	7 µg/L
2.	Upstream from Tugalo Dam:	7 µg/L

Other criteria being proposed that already exist for these lakes included pH, bacteria, dissolved oxygen, and temperature. The upper limit of the pH criteria is being revised from 8.5 to 9.0. The specific criteria being proposed are as follows:

pH: within the range of 6.0 –9.0 standard units.

Bacteria: E. coli shall not exceed the Recreation criterion as presented in 391-3-6-.03(6)(b)(i).

Dissolved Oxygen: A daily average of 5.0 mg/L and no less than 4.0 mg/L at all times at the depth specified in 391-3-6-.03(5)(g).

Temperature: Water temperature shall not exceed the Recreation criterion as presented in 391-3-6-.03(6)(b)(iv).

3.0 WATER QUALITY DATA

Lakes are generally divided into three categories of biological productivity, Oligotrophic, Mesotrophic, Eutrophic, in order of increasing productivity. Oligotrophic lakes have low nutrient inputs, with corresponding low algal biomass and high water clarity (< 2 ug/L chlorophyll *a*) during the summer growing season. These conditions tend to result in relatively low fish abundance and a visually pristine aesthetic. Eutrophic lakes have high nutrient inputs, with corresponding high algal biomass and low water clarity (> 6 ug/L chlorophyll *a*) during the summer growing season. These conditions tend to result in relatively high fish abundance and poor visual aesthetic. Mesotrophic lakes tend to fall somewhere between these two extremes with moderate levels of nutrient inputs, algal growth, clarity, and fish abundance (2 – 6 ug/L chlorophyll). Lakes Burton, Rabun, and Tugalo tend to reflect oligotrophic to mesotrophic characteristics based on the water quality data presented below.

Lakes Burton, Rabun, and Tugalo exhibit vertical thermal stratification for much of each year. As summer progresses, the warmer surface layer, or epilimnion, retains more solar energy further segregating itself from the cooler, denser waters of the hypolimnion. The epilimnion maintains higher dissolved oxygen and algal activity throughout the year and tends to be approximately 5 meters deep. The hypolimnion, or cold deep layer, exhibits low to no dissolved oxygen and little light penetration causing low to no algal activity. The photic zone, or upper layer of the lake that receives enough light penetration to allow for photosynthesis, for each lake varies in depth. Lake Burton and Rabun have average photic zone depths of 8.5 to 10 meters. Lake Tugalo has average photic zone depths between 5 and 7 meters.

In 2013, GA EPD began collecting monthly water quality samples from Lakes Burton, Rabun, and Tugalo during the growing season, from April through October. There are two monitoring locations in each of the three lakes. All water quality data for the watershed and lakes can be found in GOMAS and/or WQX. These data were used to calibrate Environmental Fluid Dynamics Code (EFDC) water quality models that were used to develop numeric water quality criteria for these lakes.

GA Power performs bacterial sampling at Timpson Cove beach on Lake Burton. Sampling occurs weekly during the peak swimming season. Historically, the peak swimming season ended in late August when the lake levels dropped, but as the start of the school year moved earlier in August, the swim season now runs from mid-May through the end of July.

United States Forest Service (USFS) operates the Lake Rabun Beach Recreation Area near the upstream end of the lake along Lake Rabun Road. The swimming beach and campground are open from April through October, and they monitor the beach weekly from Memorial day to Labor day for bacteria.

3.1 Lake Burton

Figure 3-1 shows the locations of the Lake Burton water quality stations: Tallulah River ¼ mile south of Burton Island (Mid Lake) and the Dam Pool upstream from Lake Burton Dam (Dam Pool). The monitoring sites correspond to the following monitoring location IDs: Mid Lake is

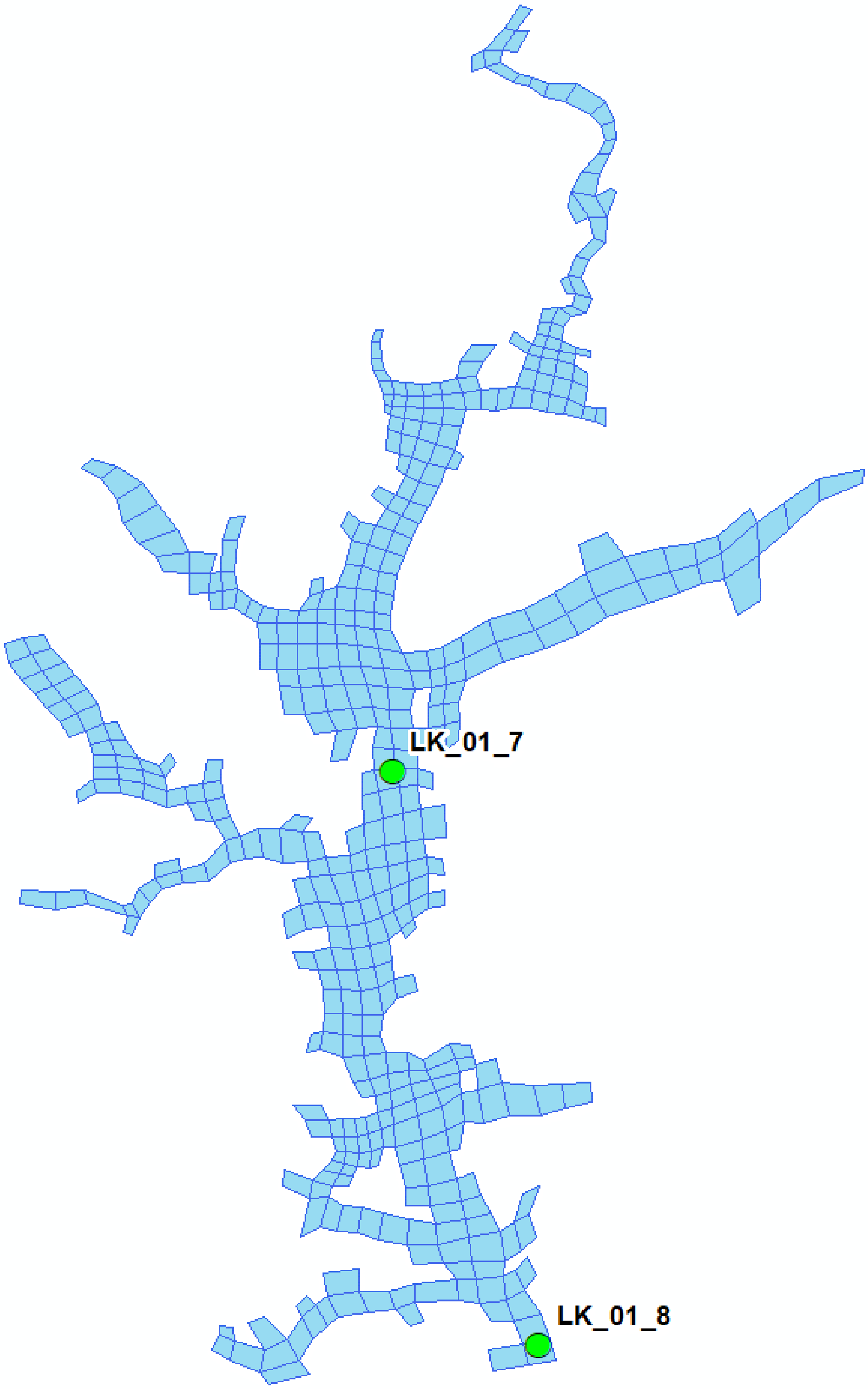


Figure 3-1. Lake Burton Monitoring Sites

LK_01_7, and the Dam Pool is LK_01_8. The location names and IDs are used interchangeably in the following figures.

Figure 3-2 shows measured chlorophyll *a* data from 2013 to 2023 at both stations. This plot shows chlorophyll *a* levels in the lake vary throughout the growing season and from year to year, with levels decreasing over the last three years.

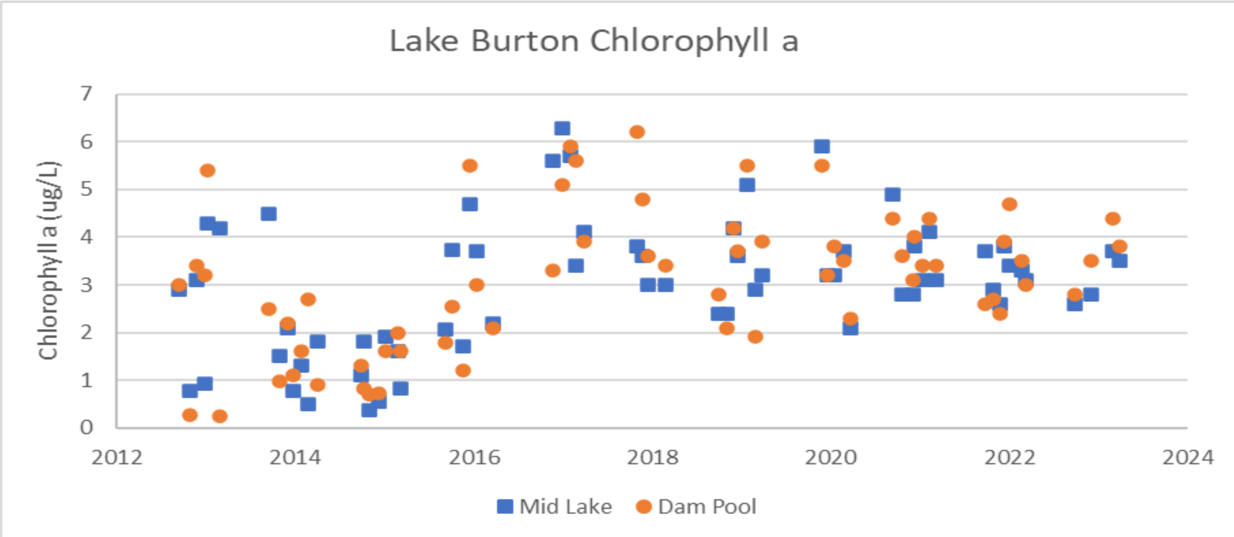


Figure 3-2. Lake Burton Measured Chlorophyll A Data 2013 – 2023

There was significantly more rainfall in 2009, 2013, 2018, and 2020 compared to the average annual rainfall (Figure 3-3). This higher rainfall may have resulted in higher chlorophyll *a* levels in the lakes due to larger nutrient contributions from nonpoint source runoff. In 2019, the chlorophyll *a* levels may have been higher due to the high nutrient fluxes from the lake bottom sediments releasing nutrients into the water column as a result of higher level of nutrients entering the lake in 2018.

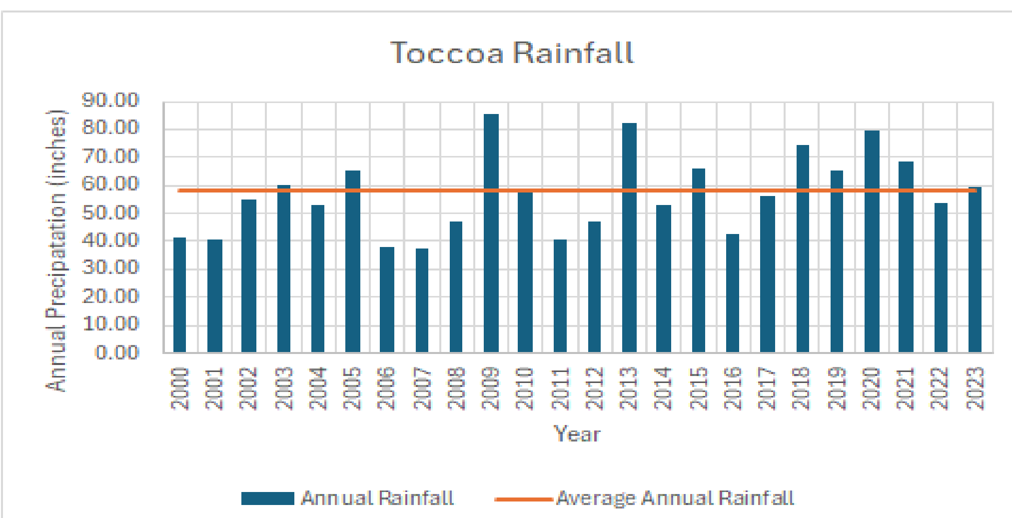


Figure 3-3. Monthly Rainfall Measured at Toccoa, Georgia

Figures 3-4 and 3-5 show the measured chlorophyll *a* and growing season average chlorophyll *a* levels at each station for the years 2013-2023, along with the proposed criteria. The proposed criteria are slightly lower than some of the measured chlorophyll *a* levels, but slightly higher than the growing season average chlorophyll *a* levels.

Figure 3-6 shows measured total nitrogen data from 1984 to 2023 at the Dam Pool station and the measured data from 2002 to 2023 at the Mid Lake Station. Figure 3-7 shows measured total phosphorus data from 2002 to 2023 at both stations. These plots may indicate that the Total Nitrogen and Total Phosphorus levels are fairly consistent over time, which is to be expected since there is only one small point source dischargers in Lake Burton.

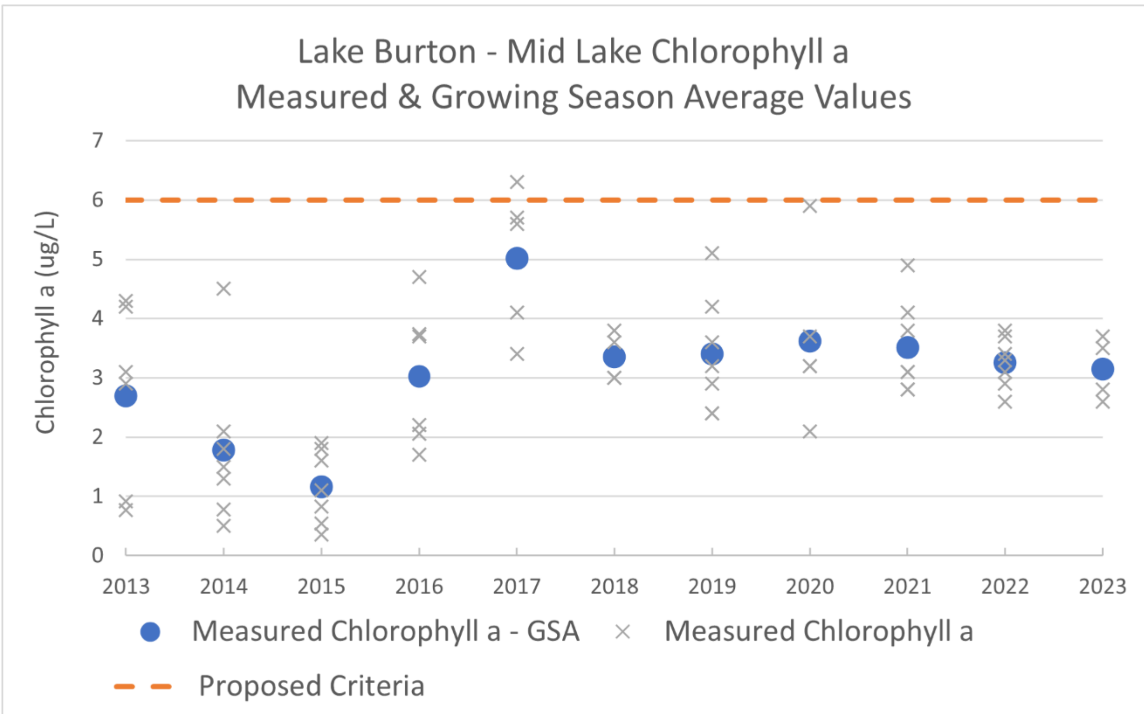


Figure 3-4. Measured Chlorophyll A, Growing Season Averages, And Proposed Criteria at Lake Burton – ¼ Mile South Of Burton Island (Mid Lake)

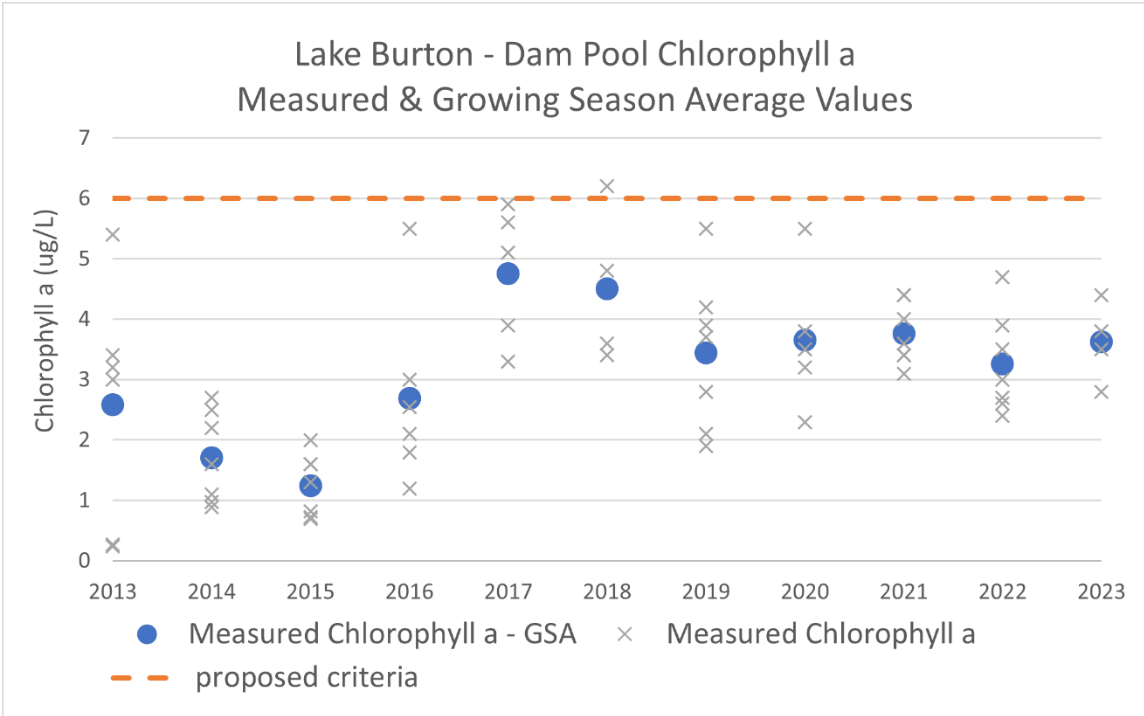


Figure 3-5. Measured Chlorophyll A, Growing Season Averages, And Proposed Criteria at Lake Burton - Dam Pool

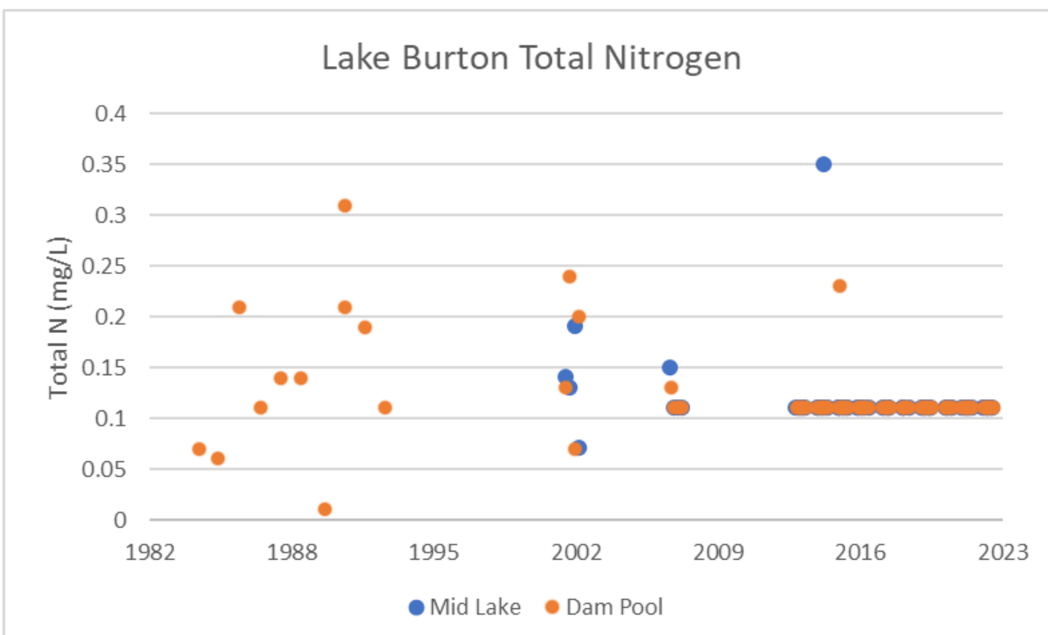


Figure 3-6. Lake Burton Measured Total Nitrogen Data 1984 – 2023

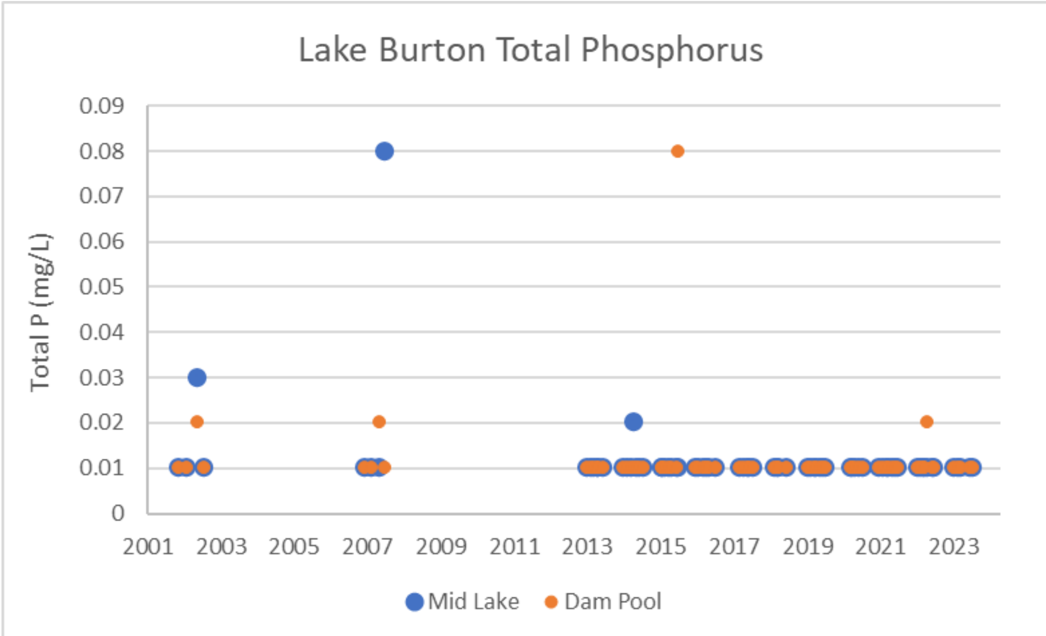


Figure 3-7. Lake Burton Measured Total Phosphorus Data 2002 – 2023

Figure 3-8 shows measured pH data from 1980 to 2024 at Lake Burton Dam Pool and pH data from 2002 to 2024 at the Mid Lake. This plot shows one pH measurement that was slightly below 6.0, but historically Lake Burton has met and continues to meet its designated use.

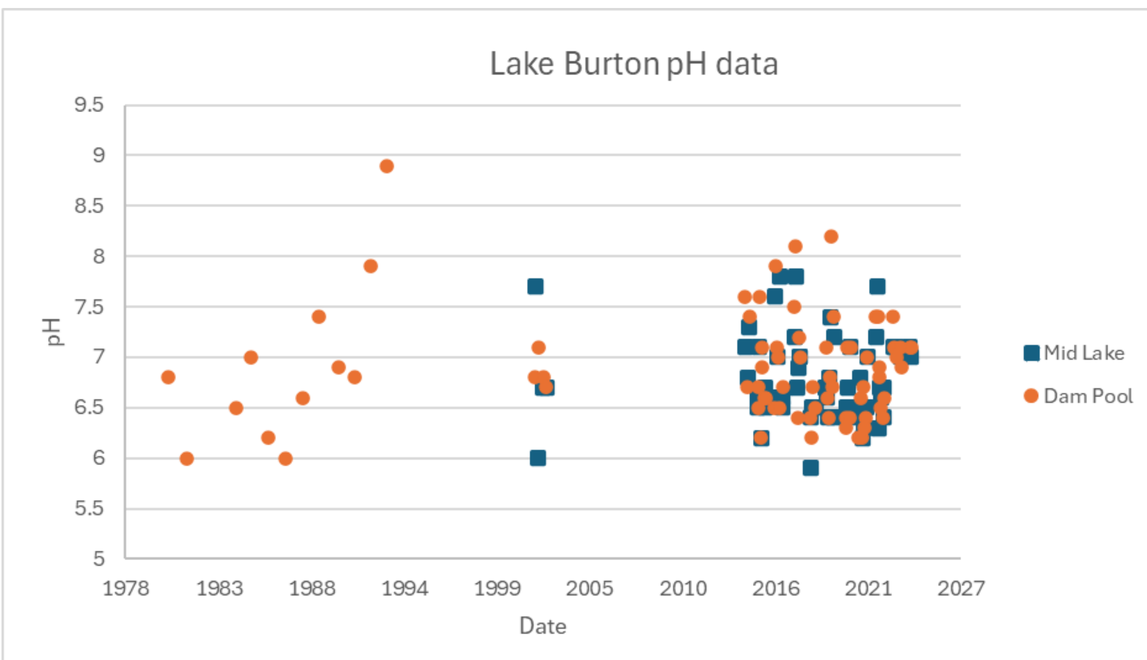


Figure 3-8. Lake Burton Measured pH Data 1980 – 2024

Figures 3-9 and 3-10 show plots of the monthly pH depth profiles for Lake Burton Mid Lake and Dam Pool, respectively, from 2014 through May of 2024. Each line represents a different year. These plots show that in the photic zone at the surface of the water column where there are higher levels of algae, the pH tends to be higher. This is the result of the removal of carbon dioxide through photosynthesis. During daylight, algae remove carbon dioxide from the water as part of the sunlight-driven process of photosynthesis. The relative rates of respiration and photosynthesis within the lake determine whether there is a net addition or removal of carbon dioxide, and therefore whether pH falls or rises. Respiration rates are affected by water temperature and the biomass of the algae, plants, animals and microorganisms in the water and bottom sediment. Rates of photosynthesis are controlled primarily by sunlight intensity, plant biomass and water temperature.

During the day, photosynthesis usually exceeds respiration, so pH rises as carbon dioxide is extracted from the water. As the sun begins to set in late afternoon, photosynthesis decreases and eventually stops, so pH falls throughout the night as respiring organisms add carbon dioxide to the water. When the sun rises, plants resume photosynthesis and remove carbon dioxide from water, causing pH to rise again. The daily interplay of respiration and photosynthesis causes pH to cycle up and down during a 24-hour period. In most aquatic environments, daily photosynthesis is about equal to respiration and pH will usually remain within a range tolerated by most organisms. The summer-time bottom pH tends to be between 6.0-6.5 and increases to around 7.0 in the spring and fall. On occasion, the bottom pH can drop below 5. However, the lake is still supporting its designated uses because the criteria are assessed at 1 meter.

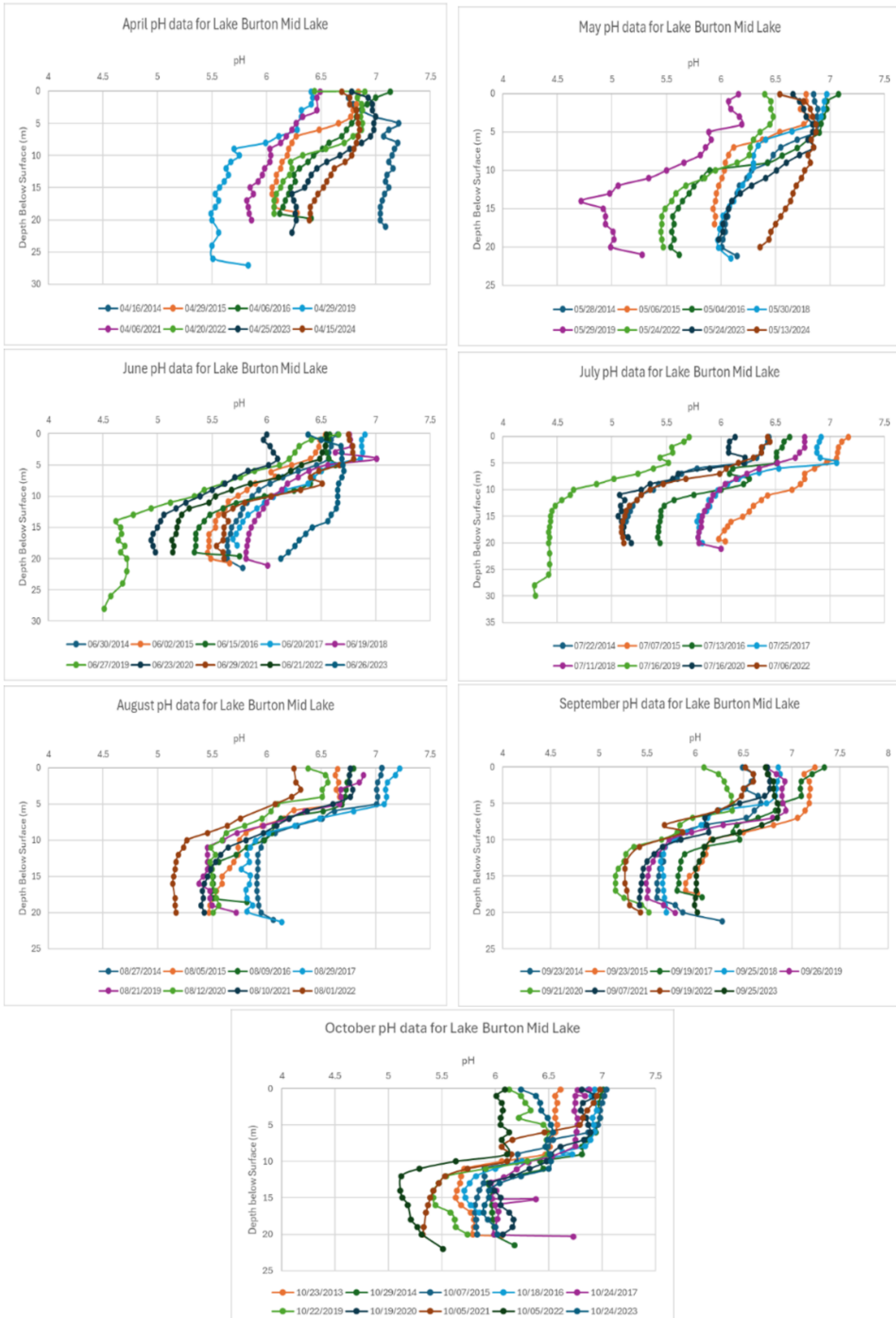


Figure 3-9. Lake Burton pH Profile Data at Mid Lake 2014 – 2024

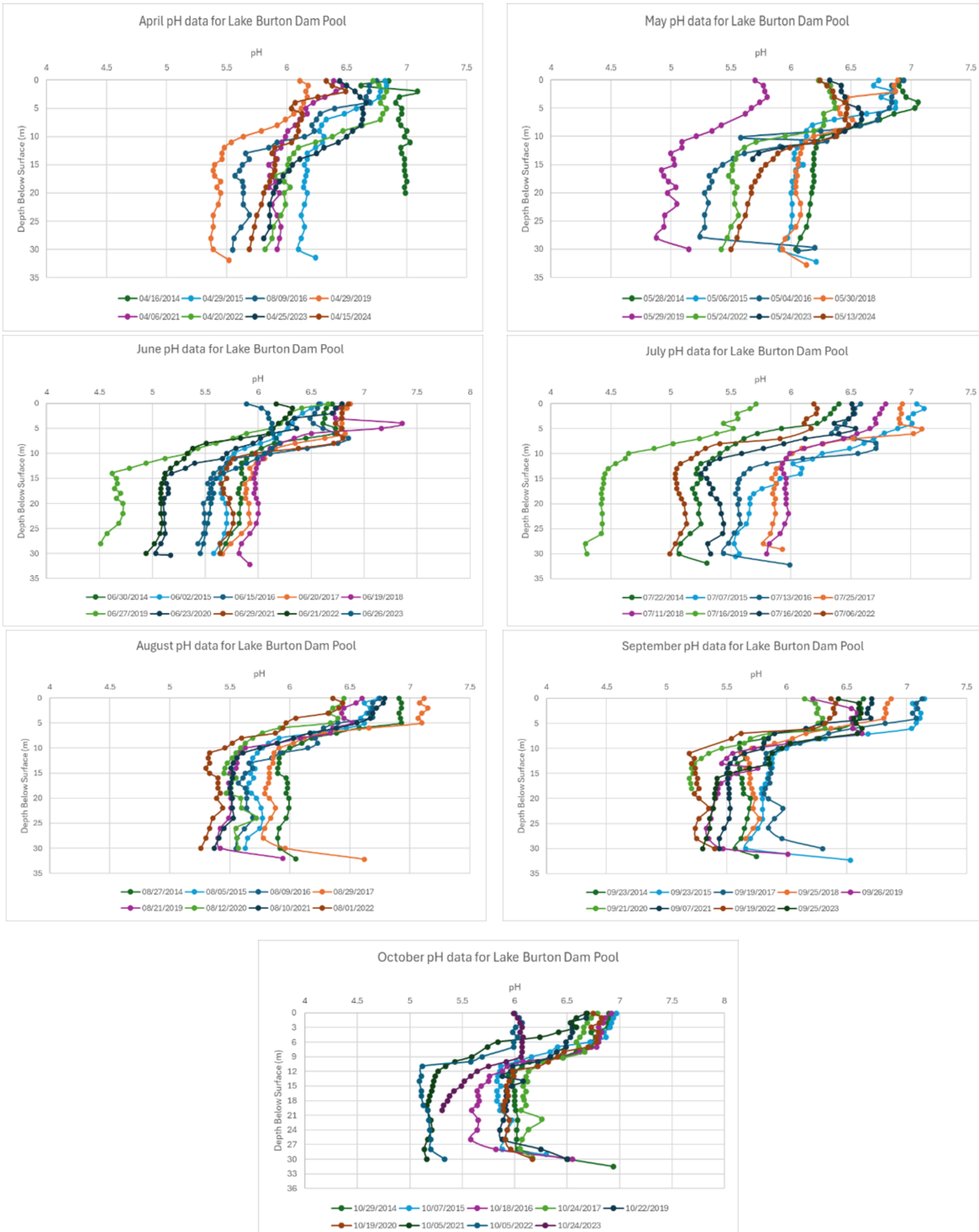


Figure 3-10. Lake Burton pH Profile Data at Dam Pool 2014 - 2023

Figures 3-11 and 3-12 show plots of the monthly temperature profiles for Lake Burton Mid Lake and Dam Pool, respectively, from 2014 through May of 2024. Each line represents a different year. Lake Burton has a strong thermocline between 5 and 10 meters. The temperature criteria of 90 deg F (32.2 deg C) was not exceeded, indicating that the lake is supporting its designated uses.

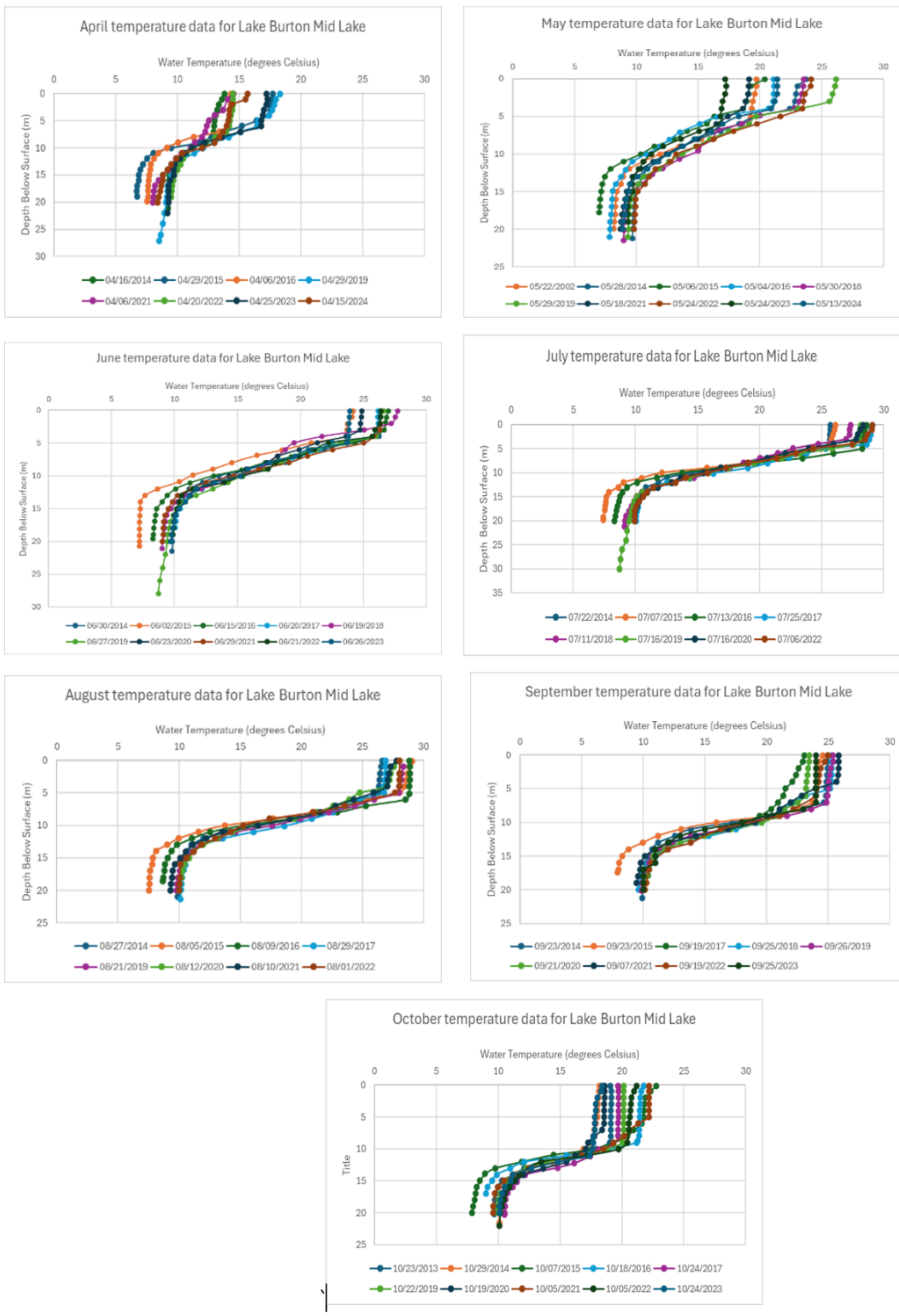


Figure 3-11. Lake Burton Temperature Profile Data at Mid Lake 2014 – 2024

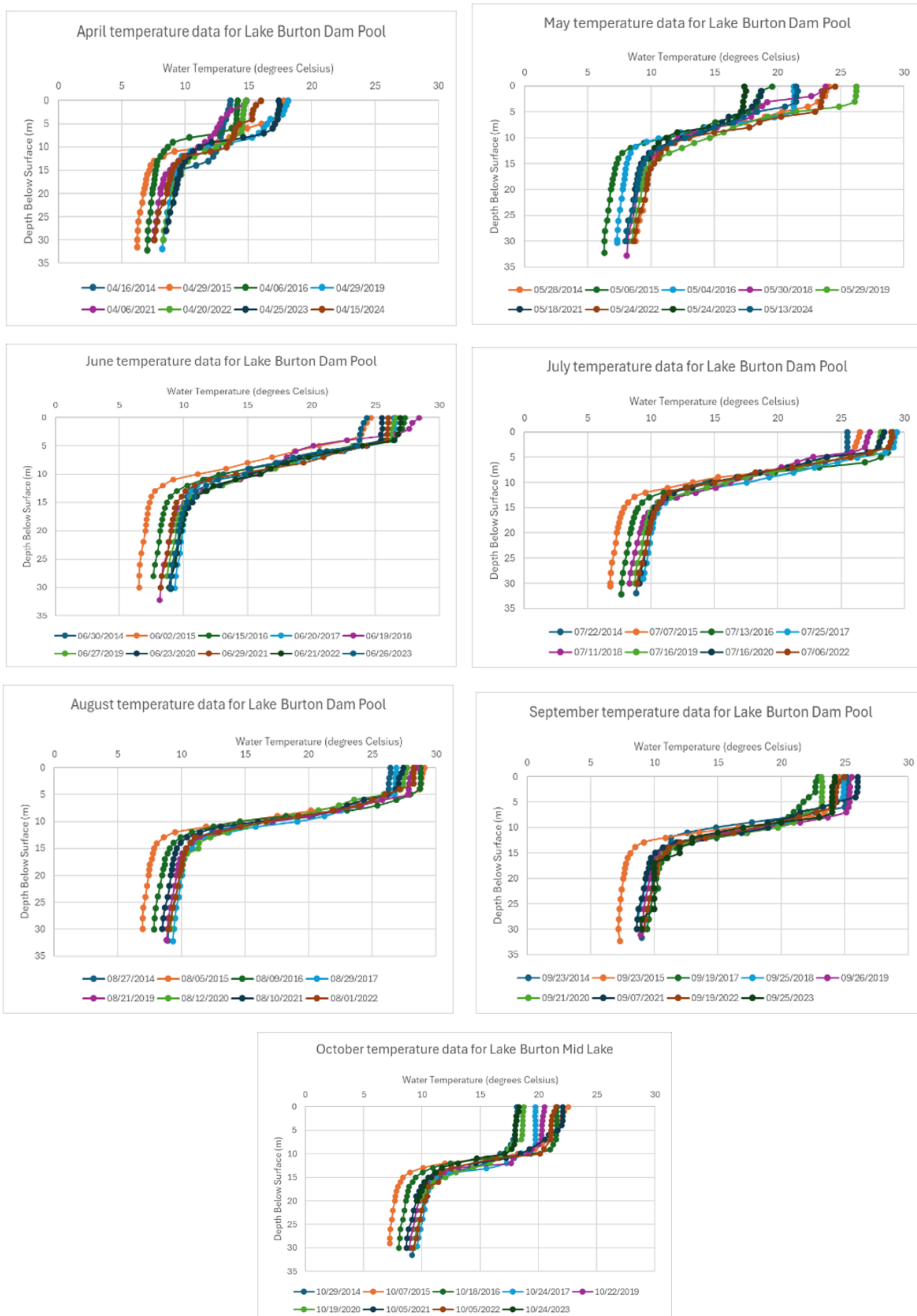


Figure 3-12. Lake Burton Temperature Profile Data at Dam Pool 2014 – 2024

The temperatures are coolest in the spring (April) and increase as the summer progresses. Temperatures then begin to decrease starting in September. Typically, the temperatures are hotter at the water surface. During the ten years of data collection, the temperatures did not exceed the 90 deg F (32.2 Deg C) criteria at either station. The lake is meeting its designated uses.

Figure 3-13 shows dissolved oxygen (DO) data measured at Lake Burton at a depth of one meter below the water surface from 2002 to 2024. The instantaneous DO at the one-meter depth meets the DO water quality criteria of a daily average of 5 mg/L and no less than 4.0 mg/L at all times, therefore the lake is supporting its designated uses.

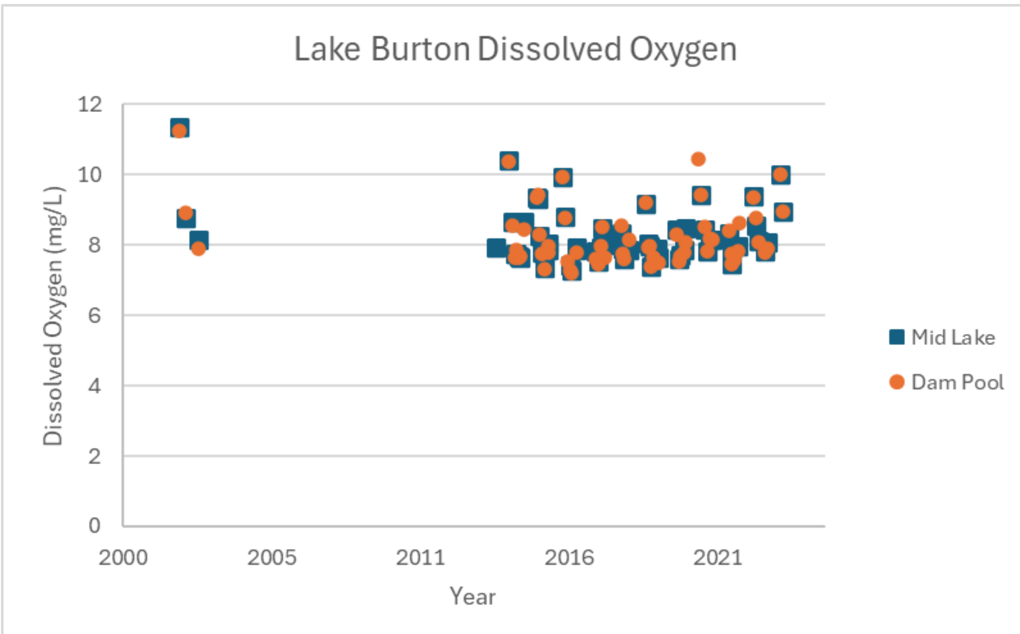


Figure 3-13. Lake Burton Measured Dissolved Oxygen Data 2002 – 2024

Figures 3-14 and 3-15 display monthly dissolved oxygen (DO) depth profiles for the Mid Lake and Dam Pool monitoring locations, respectively. Each line represents a different year. The DO tends to drop below the thermocline. The higher DO levels observed between 5 and 10 meter are probably due to algal photosynthesis and the low DO levels observed at the 10 meter depth in the Dam Pool are probably due to the dam release.

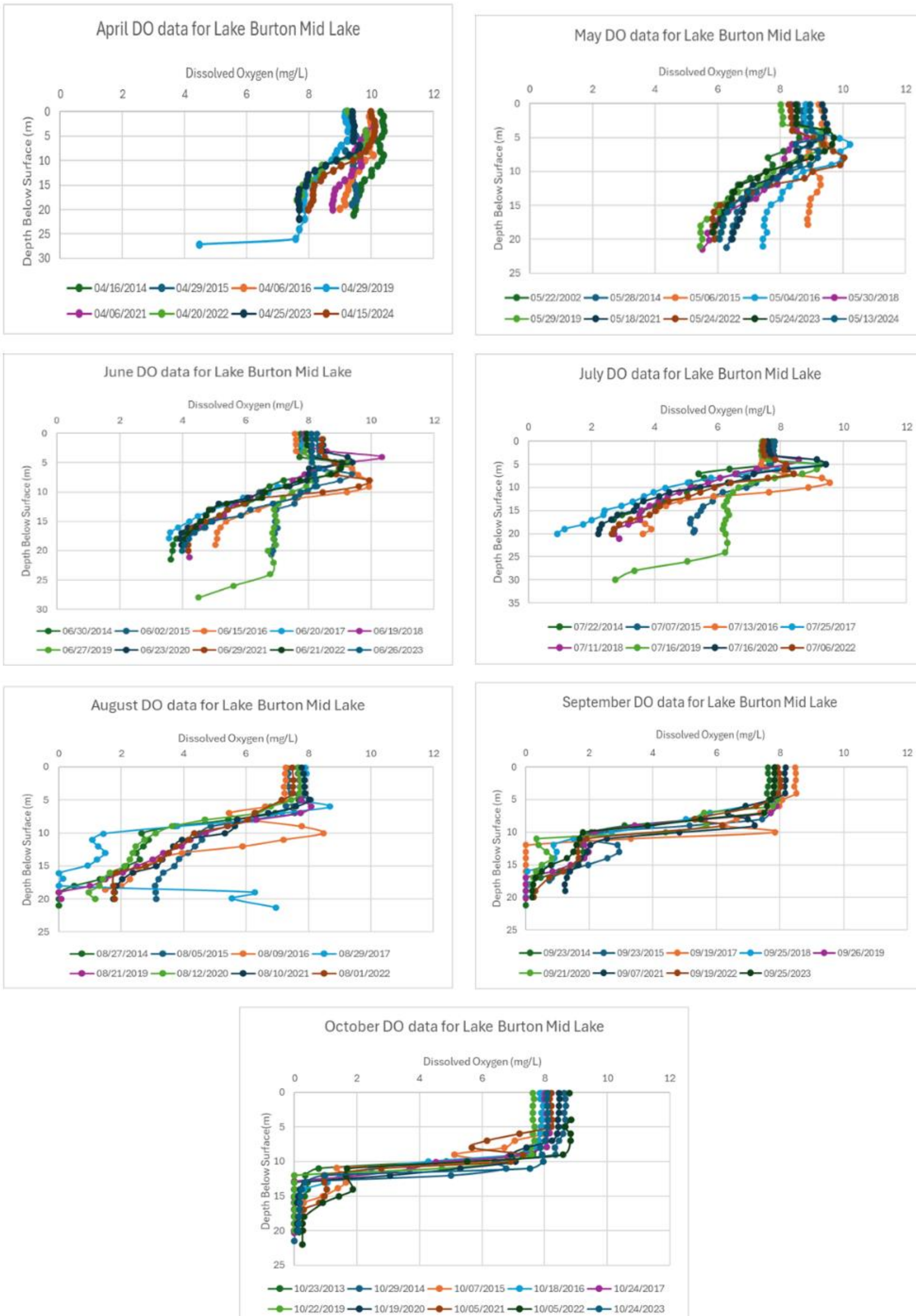


Figure 3-14. Lake Burton Mid Lake Dissolved Oxygen Profile Data 2013 – 2024

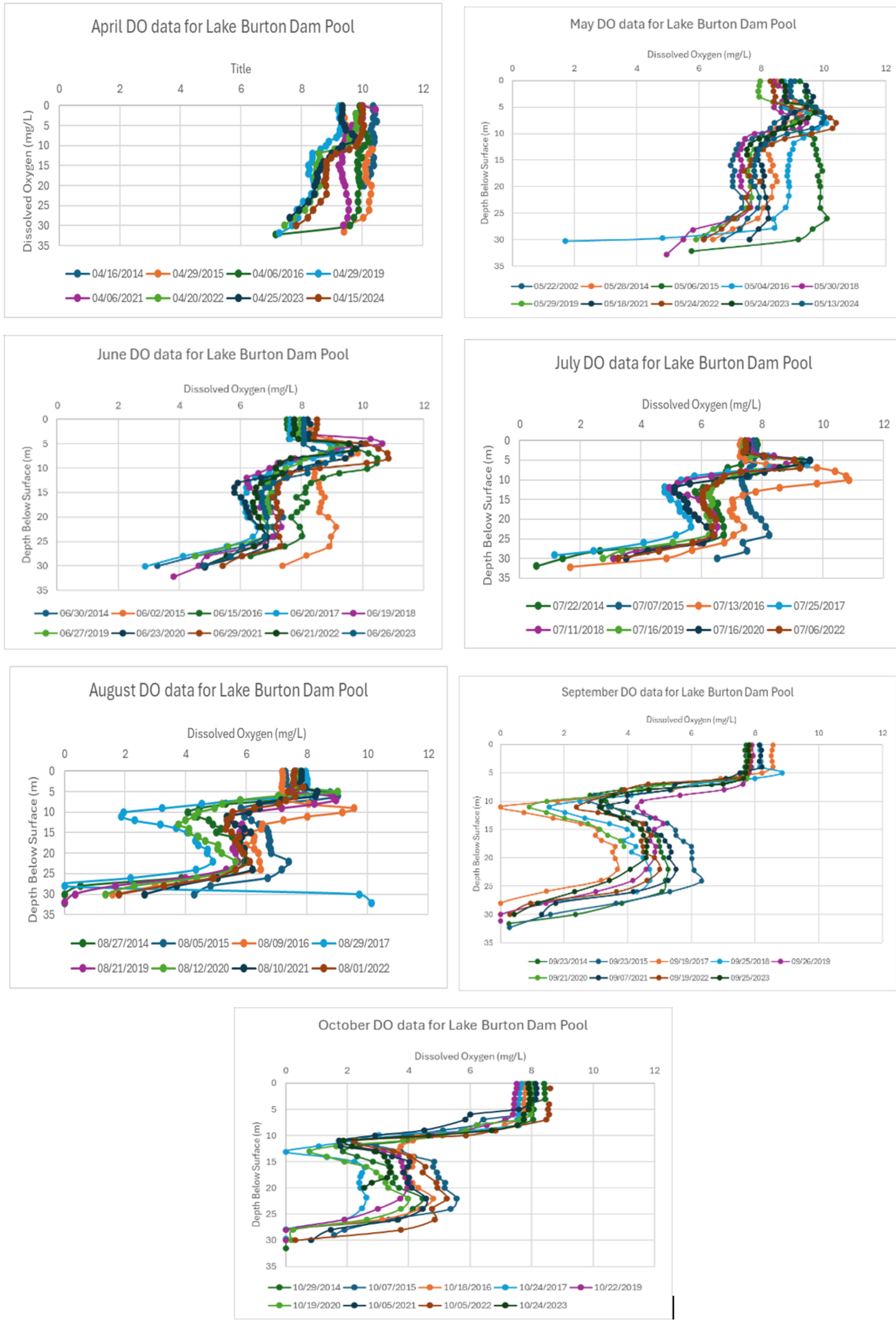


Figure 3-15. Lake Burton Dam Pool Dissolved Oxygen Profile Data 2013 – 2024

Figure 3-16 is a plot of the E. coli levels measured in Lake Burton above the detection limit. These data are from grab samples collected at the surface of the lake. Fifty-two samples were collected at the Mid Lake monitoring station over an eleven-year period. Forty-six of these samples detected no E. coli, with a reporting limit of 20 MPN/100 mL. Fifty-one samples were collected at the Dam Pool station in the same period, forty-four of which detected no E. coli. Figure 3-16 displays only samples in which E. coli was detected. None of these single monthly samples exceeded the Statistical Threshold Value of 410 E. coli counts/100 mL or the 30-day geometric mean E. coli criteria (126 counts/100 mL) that supports primary recreation, which indicates that Lake Burton is meeting its designated uses.

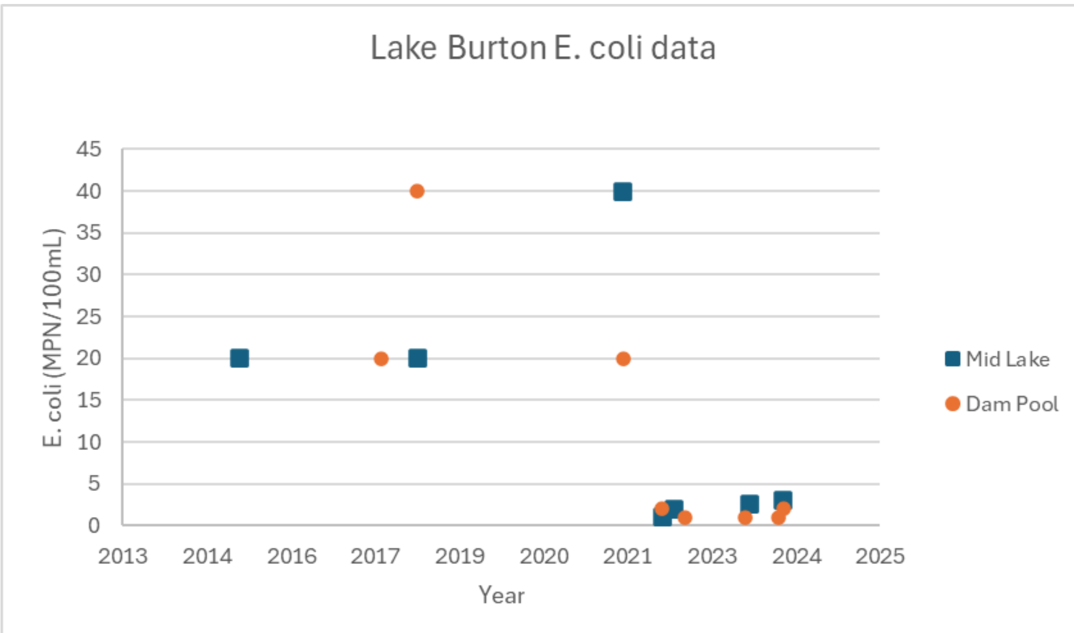


Figure 3-16. Lake Burton Measured E. Coli Data 2014 – 2024

Figure 3-17 is a plot of fecal coliform levels measured in Lake Burton above the detection limit. These data are from grab samples collected at the surface of the lake. Sixty-eight samples were collected at the Mid Lake monitoring station between 2007 and 2017. Fifty-seven of these samples detected no fecal coliform, with a reporting limit of 20 MPN/100 mL. Sixty-one samples were collected at the Dam Pool station between 1984 and 2017, fifty-six of which detected no fecal coliform. Figure 3-17 displays only samples in which fecal coliform was detected. None of these single monthly samples exceeded the 30-day geometric mean fecal coliform criteria (200 counts/100 mL) that supported primary recreation prior to the change to E. coli as the bacteria indicator for recreation designated use in 2015. These data demonstrate that Lake Burton has historically met its designated uses.

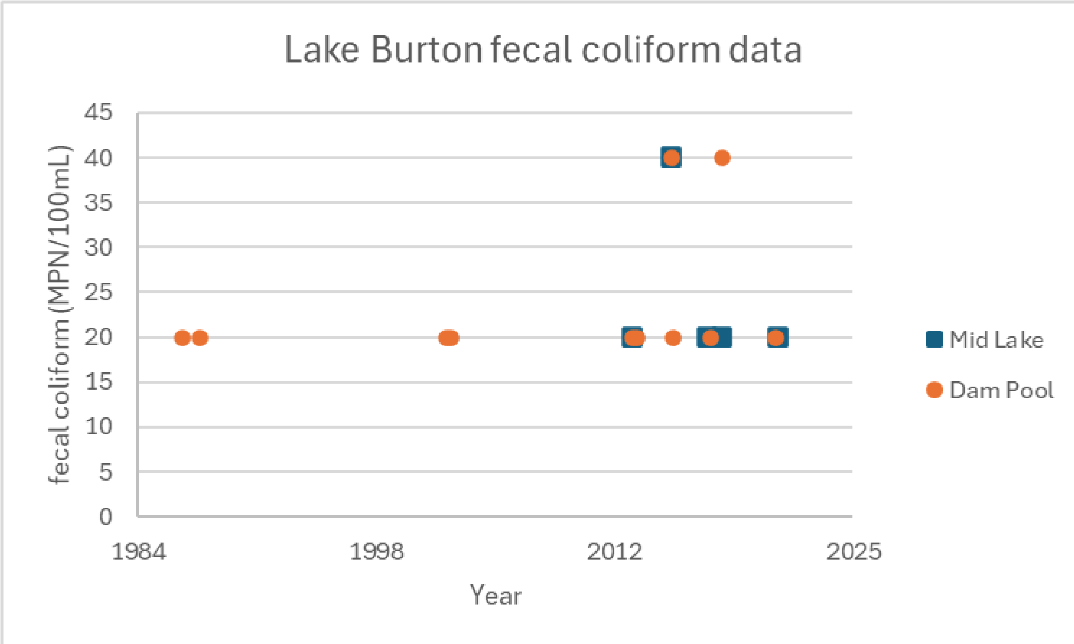


Figure 3-17. Lake Burton Measured fecal coliform Data 1984 – 2017

3.2 Lake Rabun

Figure 3-18 shows the locations of the Lake Rabun water quality stations: Approx. 4.5 mi u/s Dam (Mid Lake), and Dam Pool (aka Tallulah River - Upstream from Mathis Dam). The monitoring sites correspond to the following monitoring location IDs: Mid Lake is LK_01_9 and Dam Pool is LK_01_10. The location names and IDs are used interchangeably in the following figures.

Figure 3-19 shows measured chlorophyll a data from 2002 to 2023 at both stations. This plot shows chlorophyll a levels in the lake vary throughout the growing season and year to year, and rarely exceed 6 µg/L.

Figures 3-20 and 3-21 present the chlorophyll a measured at each station compared to growing season averages for the years 2013 to 2023, along with the proposed criteria. The proposed criteria are slightly less than the measured data, but greater than the growing season averages.

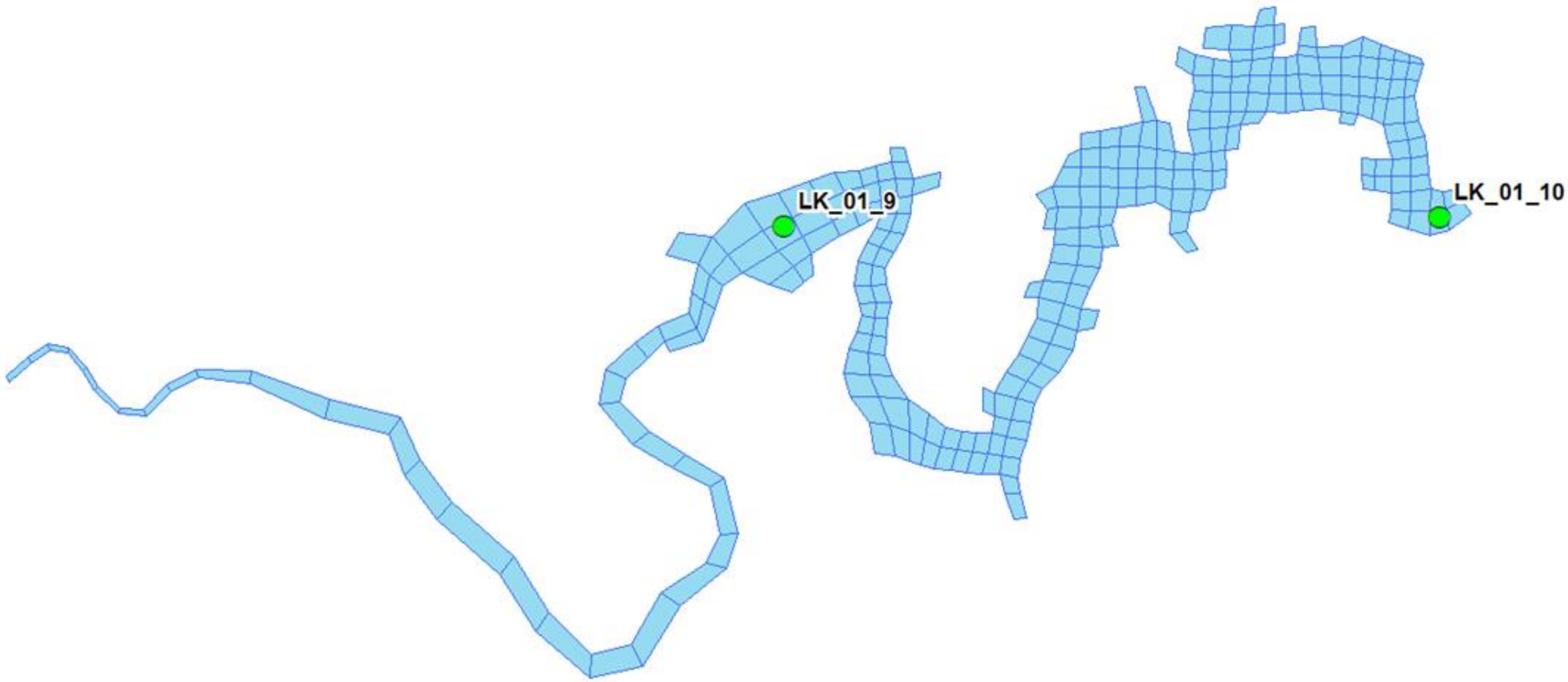


Figure 3-18. Lake Rabun Monitoring Sites

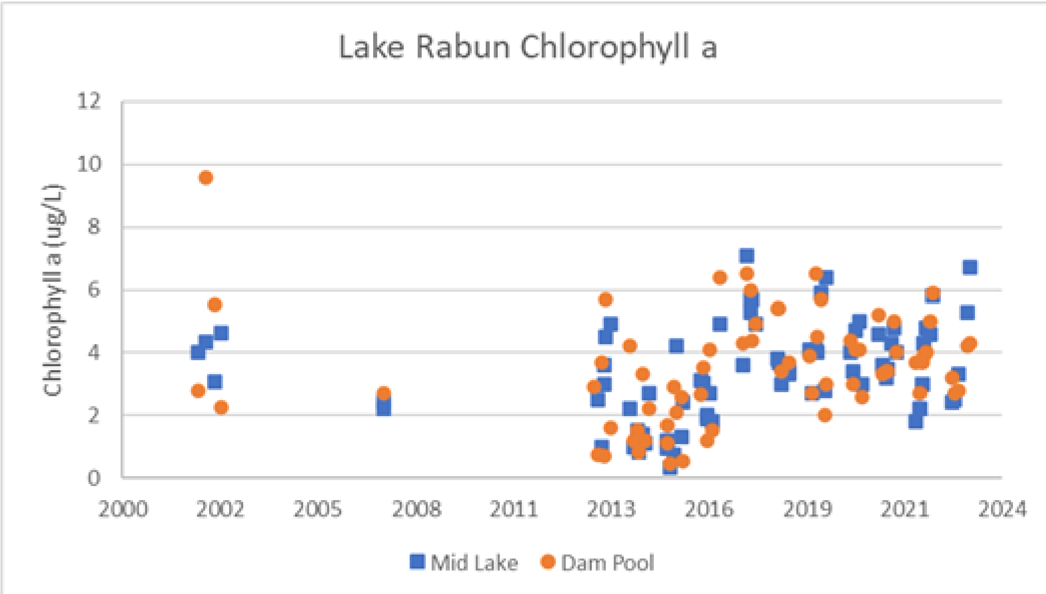


Figure 3-19. Lake Rabun Measured Chlorophyll a Data 2002 – 2023

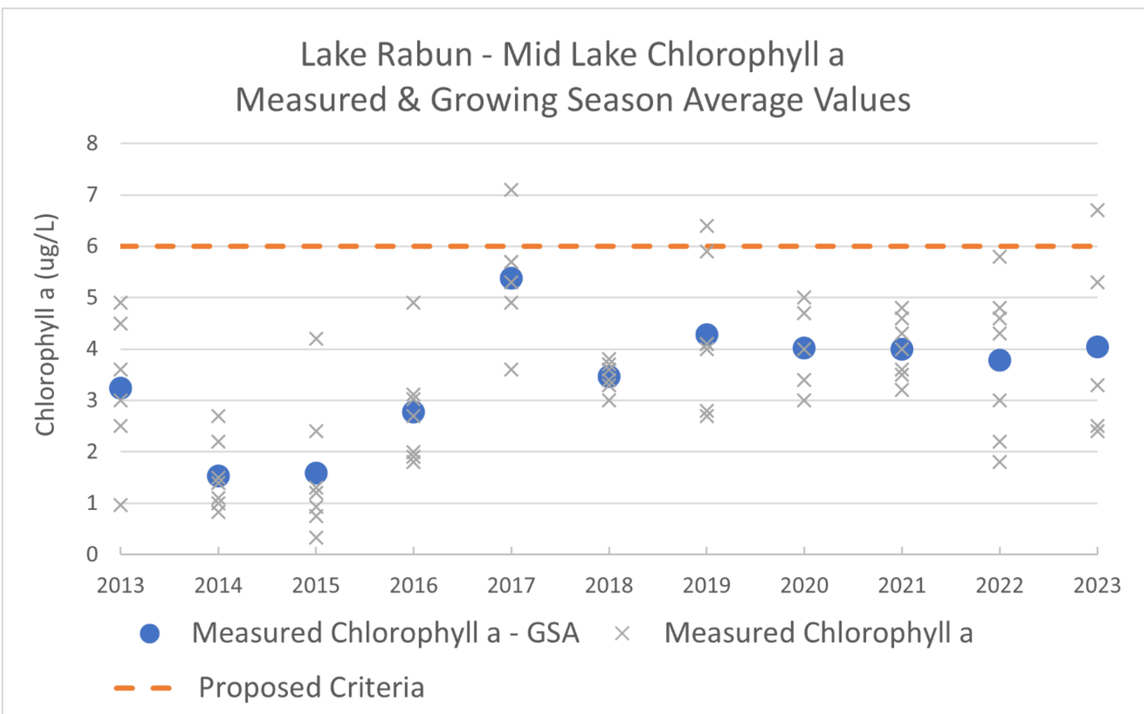


Figure 3-20. Measured Chlorophyll a, Growing Season Averages, and Proposed Criteria at Lake Rabun - Mid Lake

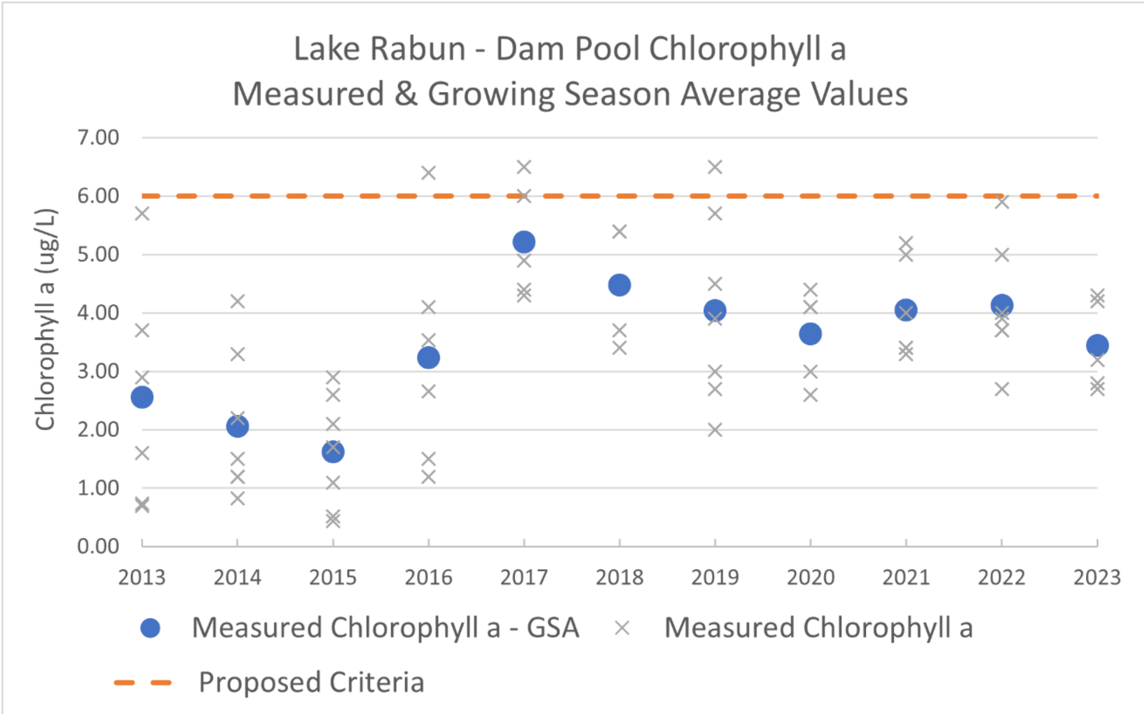


Figure 3-21. Measured Chlorophyll a, Growing Season Averages, and Proposed Criteria at Lake Rabun - Dam Pool

Figure 3-22 shows measured total nitrogen data from 2002 to 2023 at both water quality stations. Figure 3-23 shows measured total phosphorus data from 1980 to 2023 at the Dam Pool and from 2002 to 2023 at Mid Lake. It appears that the total nitrogen and total phosphorus levels are roughly the same over time.

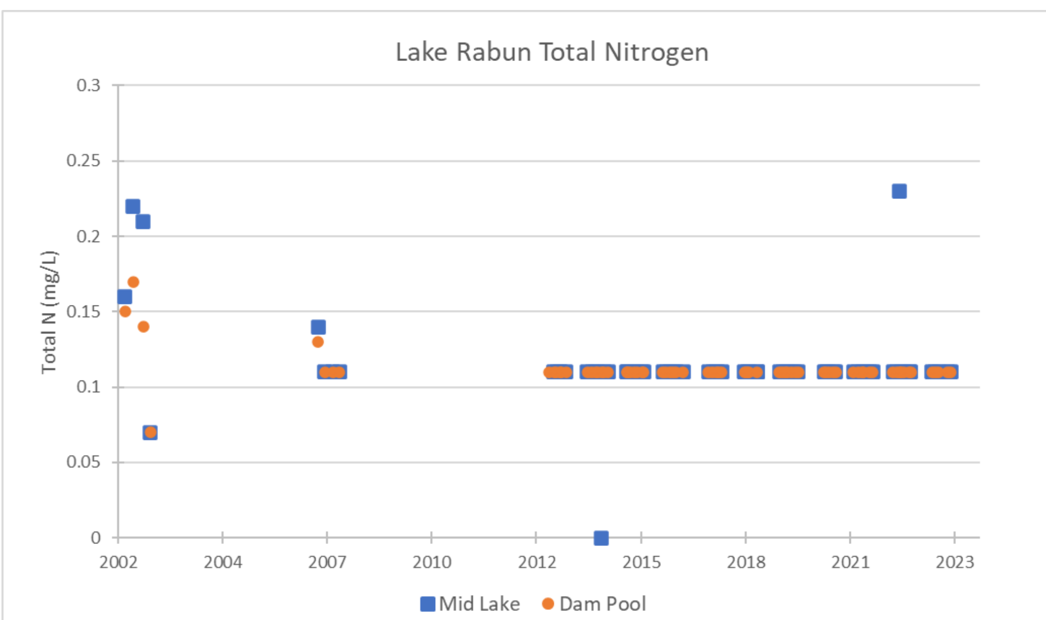


Figure 3-22. Lake Rabun Measured Total Nitrogen Data 2002 – 2023

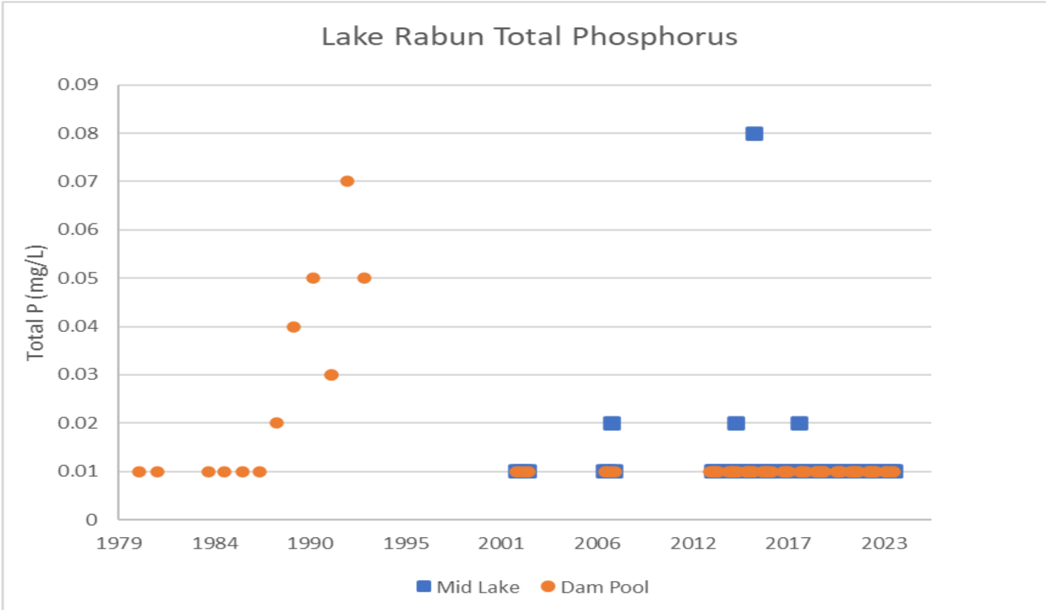


Figure 3-23. Lake Rabun Measured Total Phosphorus Data 1980 – 2023

Figure 3-24 shows measured pH data from 1980 to 2024 at both stations. This plot shows that most of the time the surface pH ranges between 6.0 and 8.5.

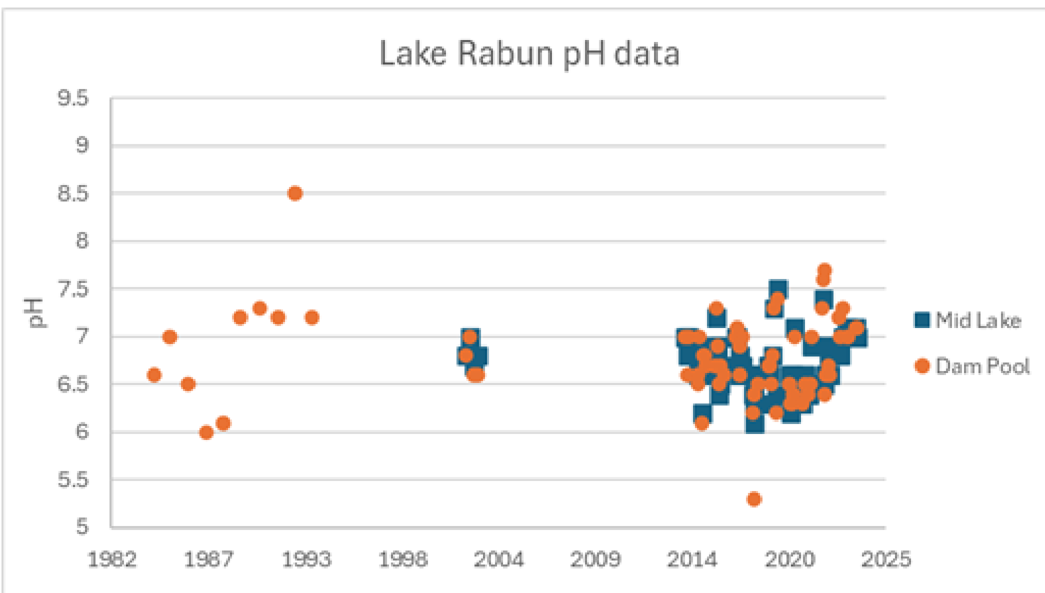


Figure 3-24. Lake Rabun Measured pH Data 1980 – 2024

Figures 3-25 and 3-26 present the monthly pH profiles at the Lake Rabun Mid Lake and Dam Pool monitoring stations respectively, from April through October. Each line represents a different year. At the Mid Lake, May is the month with the most varied pH levels. The pH is typically higher at the surface and decreases in depth. In many years, the bottom pH increased toward the end of the growing season. Lake Rabun is classified as assessment pending for low pH that may be due to low conductivity.

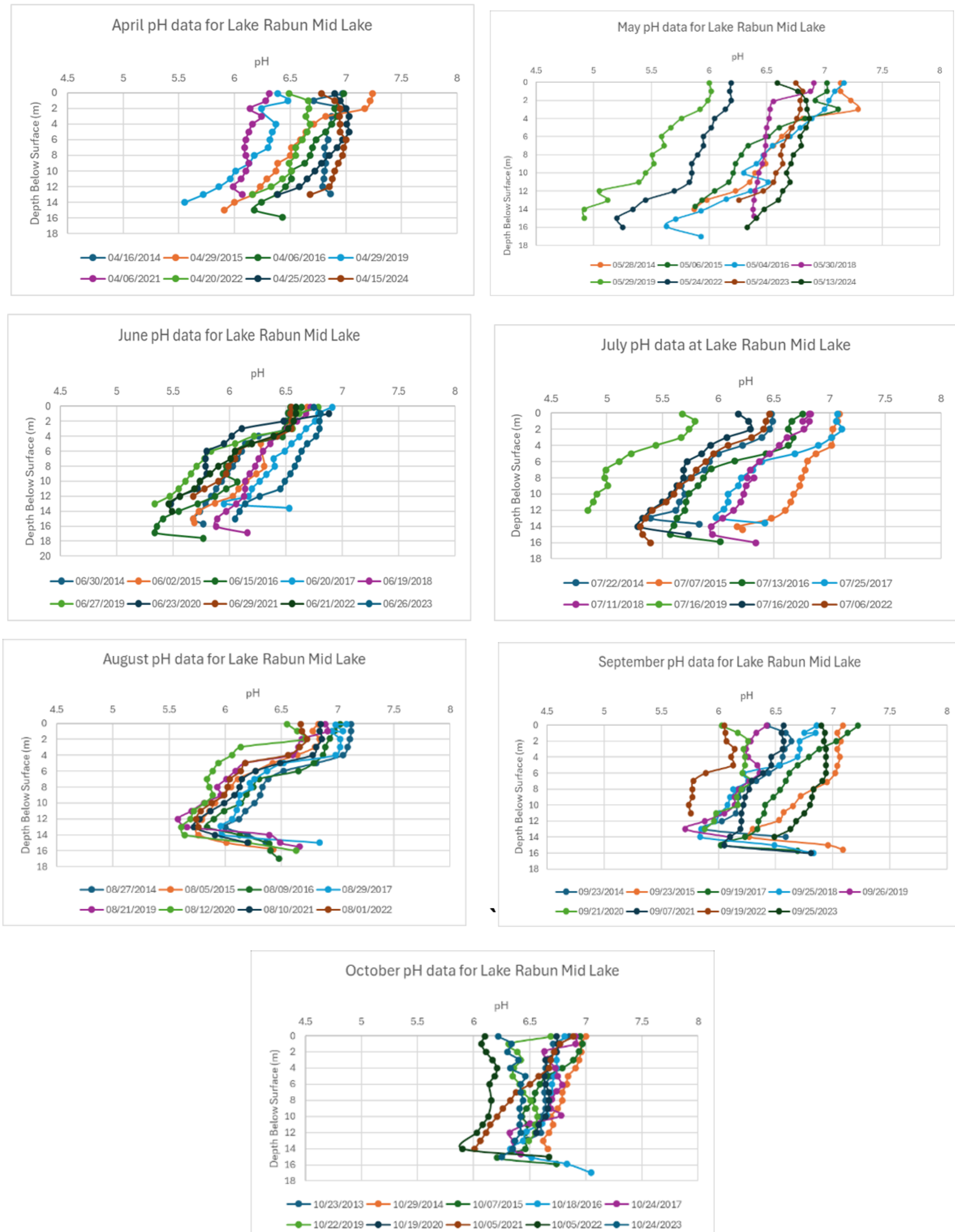


Figure 3-25. Lake Rabun pH Profile Data at Mid Lake 2013 – 2024

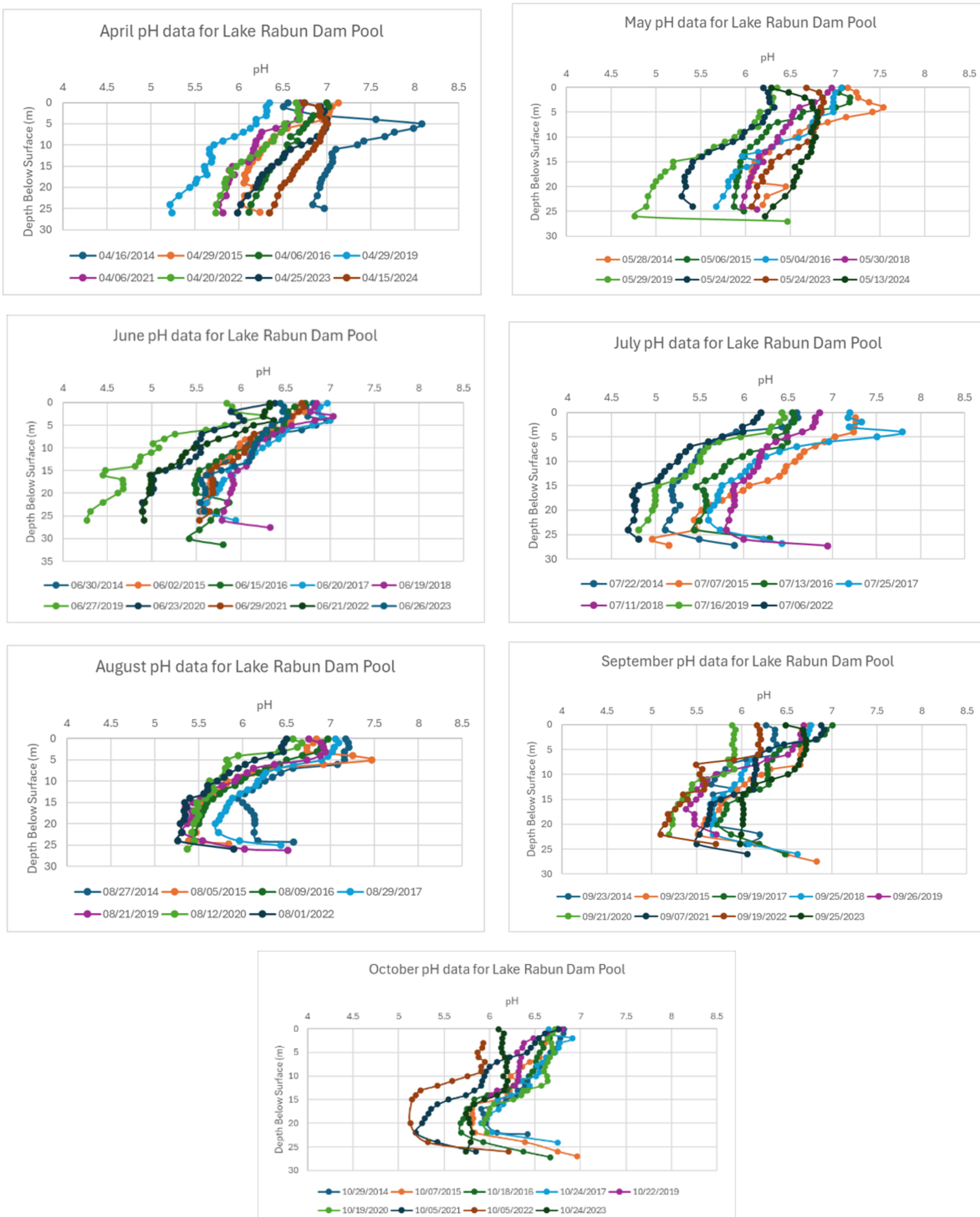


Figure 3-26. Lake Rabun pH Profile Data at Dam Pool 2002 and 2014 – 2024

Figures 3-27 and 3-28 show the temperature profile data measured in Lake Rabun at the Mid Lake and Dam Pool monitoring stations, respectively. Each line represents a different year. The temperature criteria of 90 deg F (32.2 deg C) was not exceeded, indicating that the lake is supporting its designated uses. The thermocline in Lake Rabun tends to be at a depth of 12-15 meters.

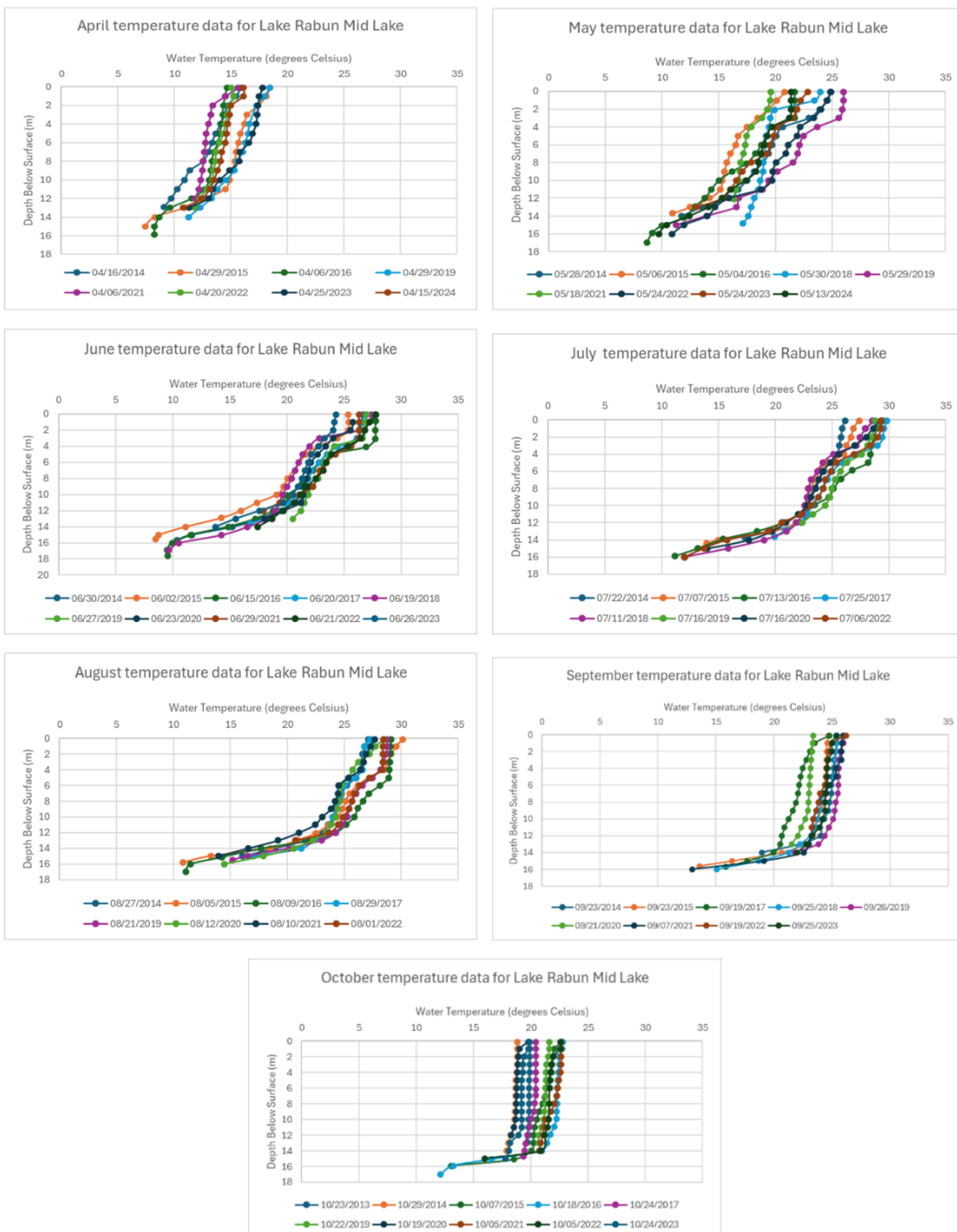


Figure 3-27. Lake Rabun Temperature Profile Data at Mid Lake 2013 – 2024

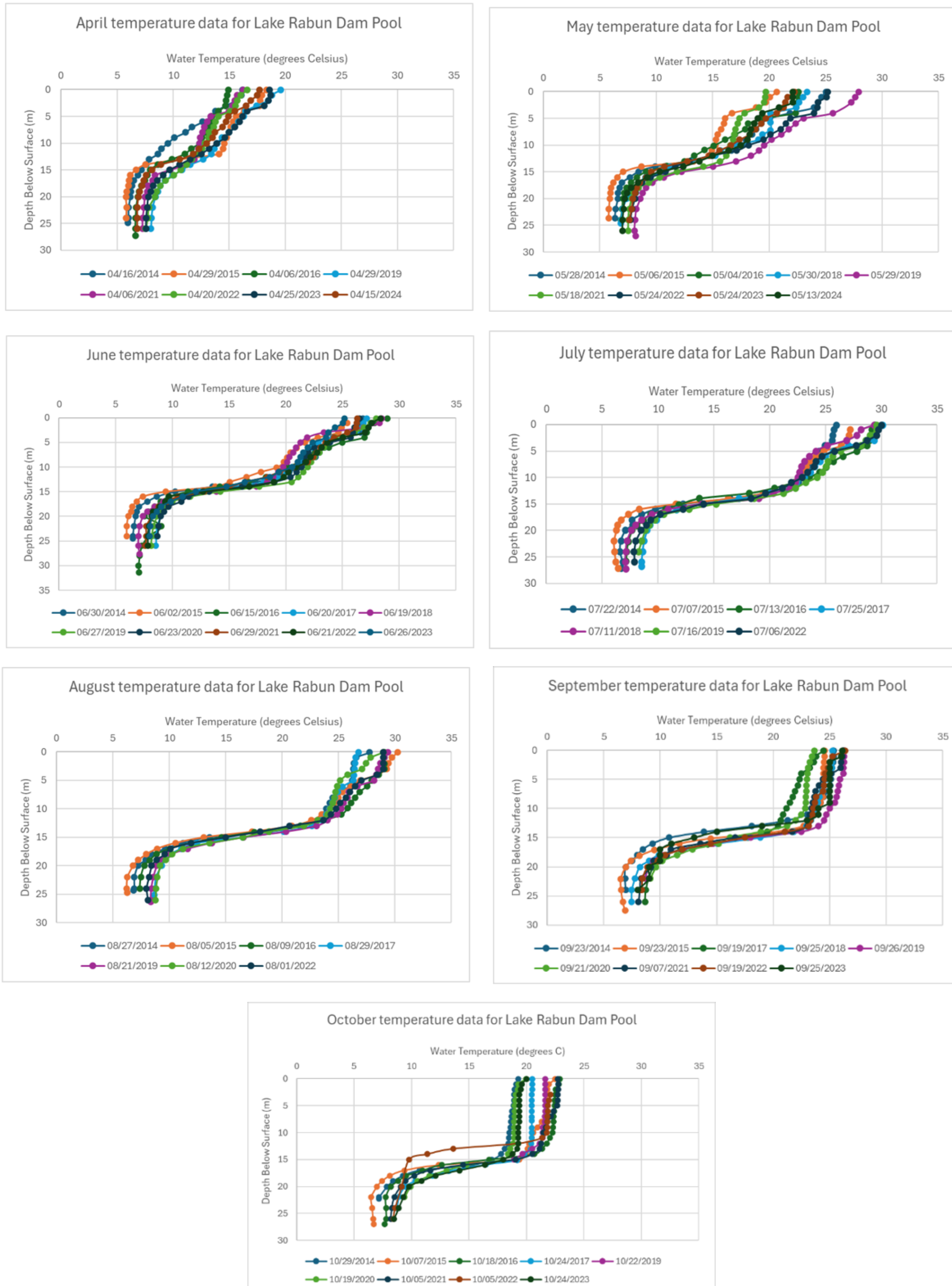


Figure 3-28.Lake Rabun Temperature Profile Data at Dam Pool 2014 – 2024

Figures 3-29 and 3-30 display dissolved oxygen depth profile data for the Mid Lake and Dam Pool monitoring locations, respectively. Each line represents a different year. The DO levels follow the thermocline at Mid Lake, but at the Dam Pool, the dam release probably causes the lower DO observed at the 15-meter depth.

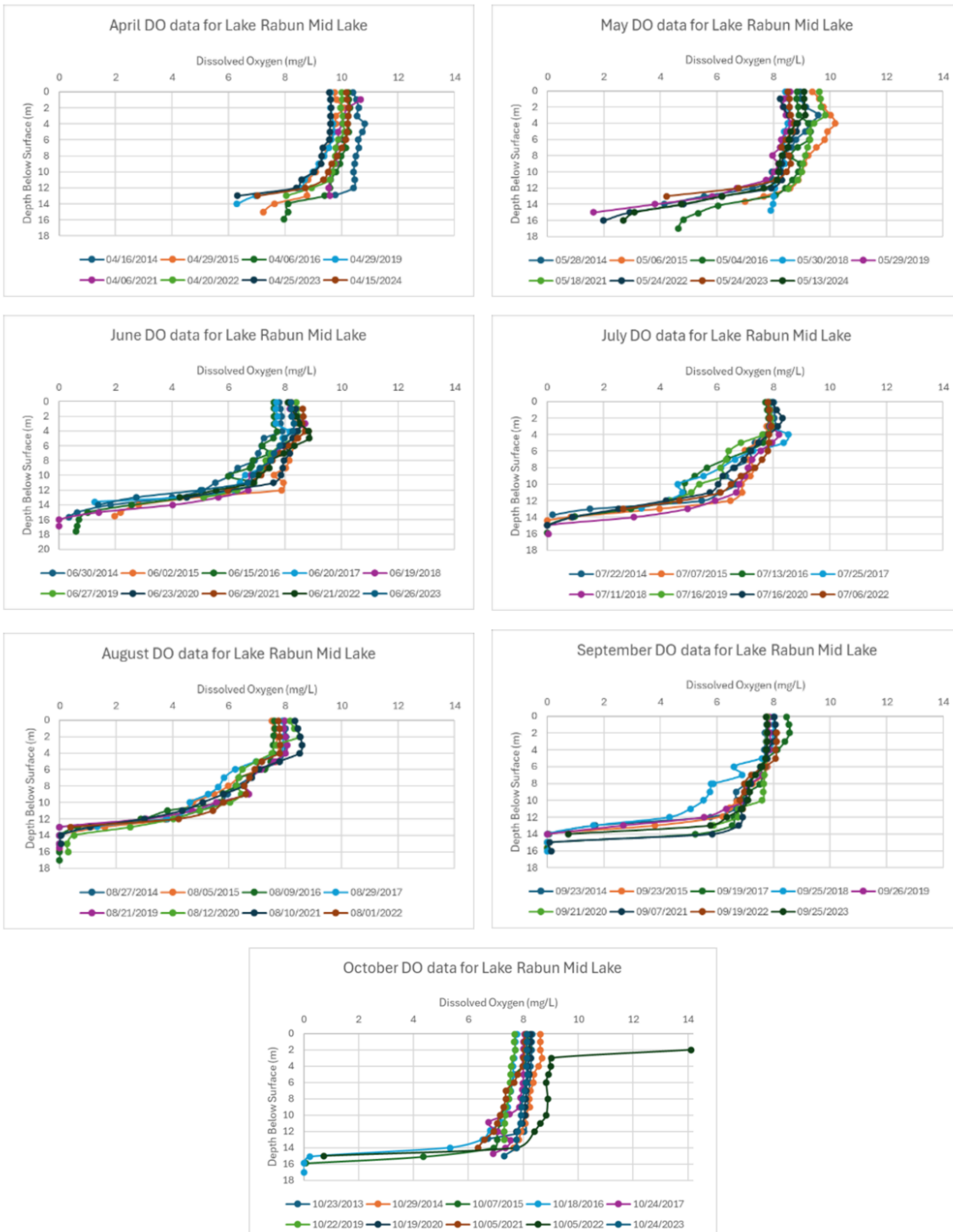


Figure 3-29. Lake Rabun Dissolved Oxygen Profile Data at Mid Lake 2013 – 2024

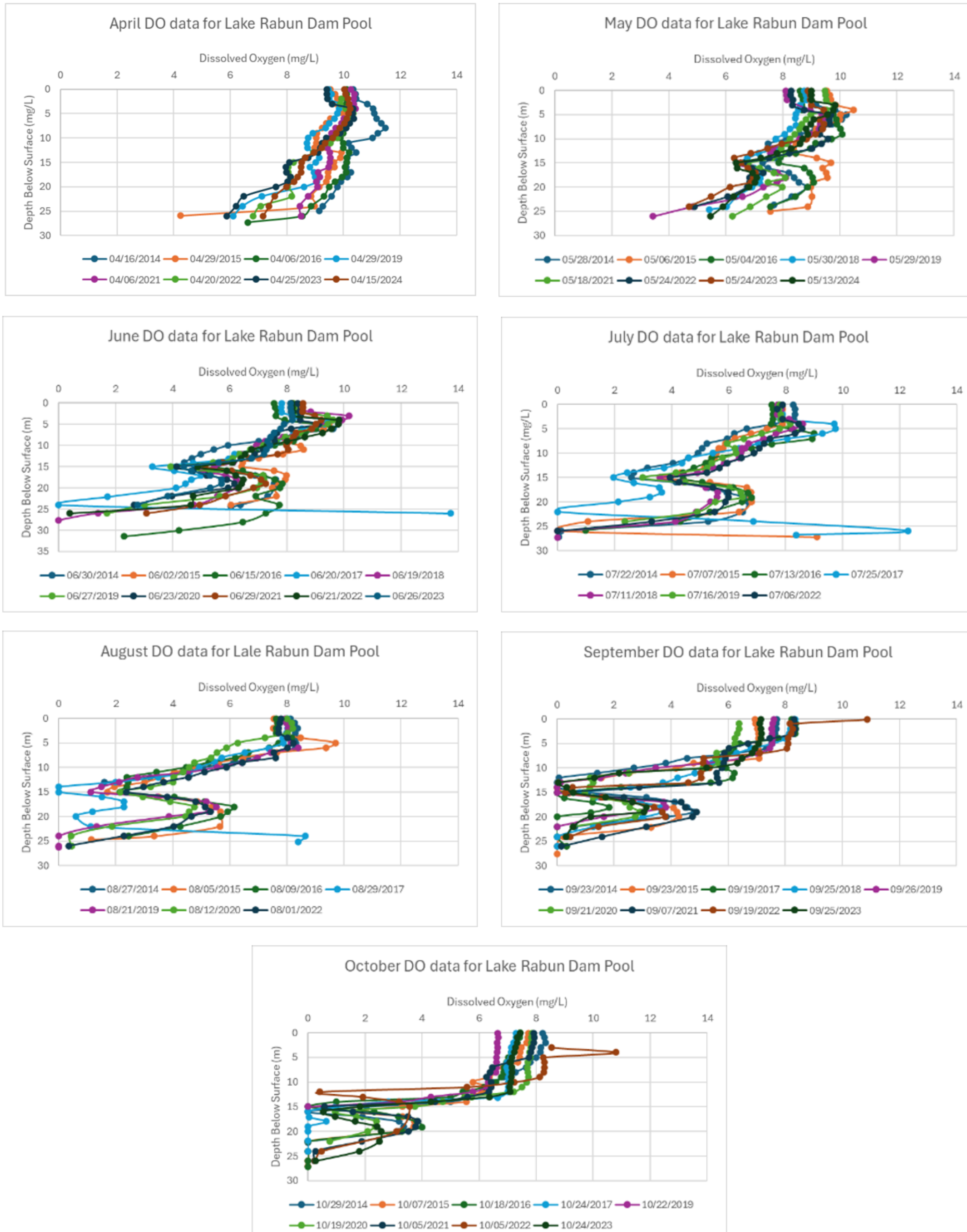


Figure 3-30. Lake Rabun Dissolved Oxygen Profile Data at Dam Pool 2013 – 2024

Figure 3-31 shows dissolved oxygen (DO) data measured at Lake Rabun at a depth of one meter below the water surface from 2002 to 2024. The instantaneous DO at the one-meter depth meets the DO water quality criteria of a daily average of 5 mg/L and no less than 4.0 mg/L at all times, therefore the lake is supporting its designated uses.

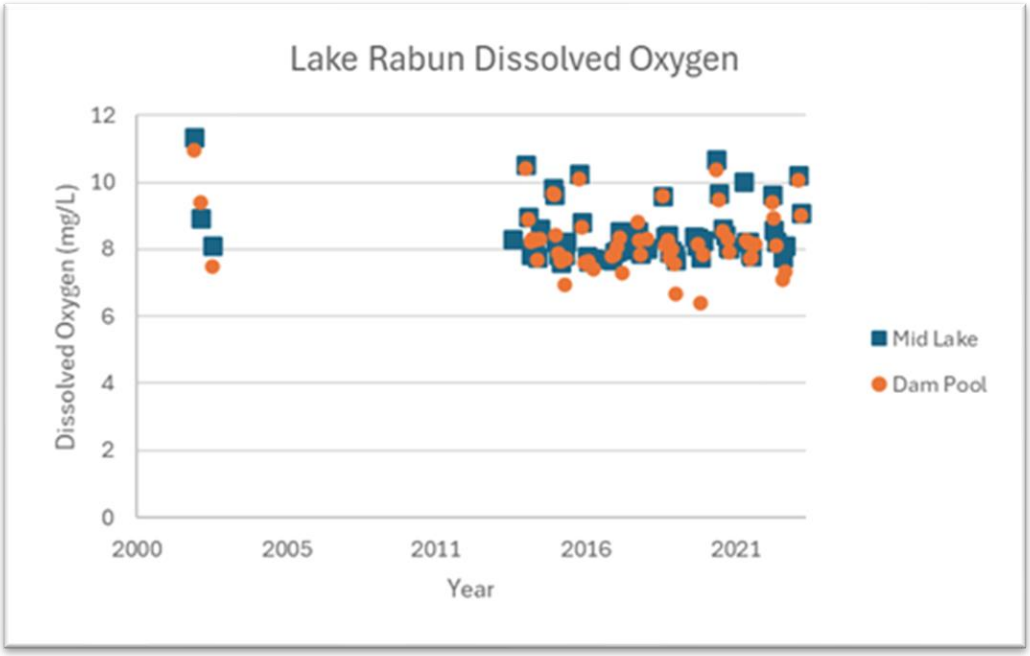


Figure 3-31. Lake Rabun Measured Dissolved Oxygen Data 2002 – 2024

Figure 3-32 is a plot of the E. coli levels measured in Lake Rabun above the detection limit. These data are from grab samples collected at the surface of the lake. Fifty-two samples were collected at the Mid Lake monitoring station over the from 2015 to May 2024. Forty-two of these samples detected no E. coli, with a reporting limit of 20 MPN/100 mL. Fifty samples were collected at the Dam Pool station in the same period, forty-three of which detected no E. coli. Figure 3-32 displays only samples in which E. coli was detected. None of these single monthly samples exceeded the Statistical Threshold Value of 410 counts/100 mL or the 30-day geometric mean E. coli criteria (126 counts/100 mL) that supports primary recreation, which indicates that Lake Rabun is meeting its designated uses.

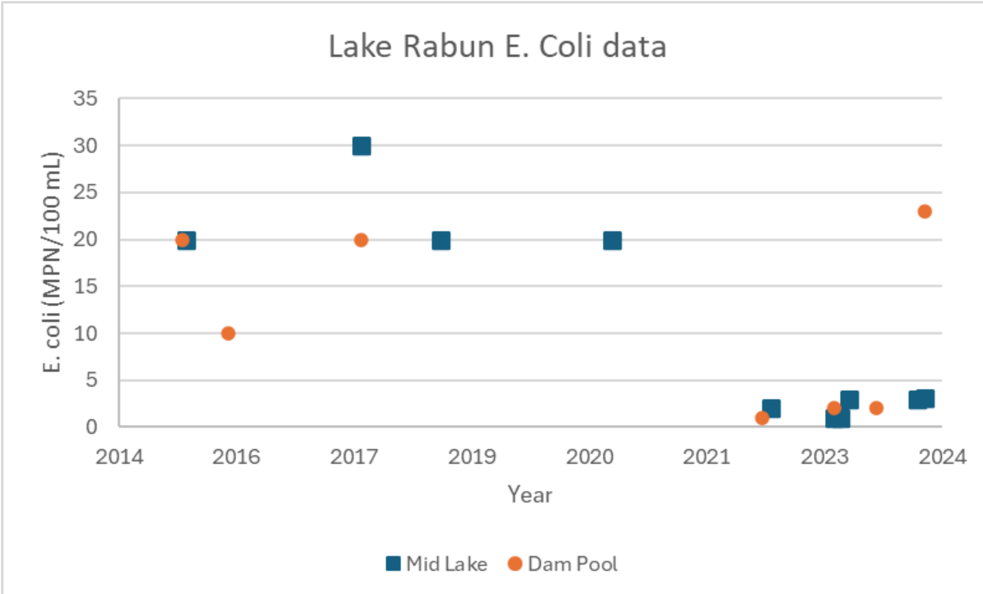


Figure 3-32. Lake Rabun Measured E. Coli Data 2015 – 2024

Figure 3-33 is a plot of fecal coliform levels measured in Lake Rabun above the detection limit. These data are from grab samples collected at the surface of the lake. Sixty samples were collected at the Mid Lake monitoring station between 2002 and 2021. Fifty-two of these samples detected no fecal coliform, with a reporting limit of 20 MPN/100 mL. Sixty-seven samples were collected at the Dam Pool station between 1984 and 2021, sixty-one detected no fecal coliform. Figure 3-37 displays only samples in which fecal coliform were detected. None of these samples exceeded the 30-day geometric mean fecal coliform criteria (200 counts/100 mL) that supported primary recreation prior to the change to E. coli as the bacteria indicator for recreation designated use in 2015. These data demonstrate that Lake Rabun has historically met its designated uses.

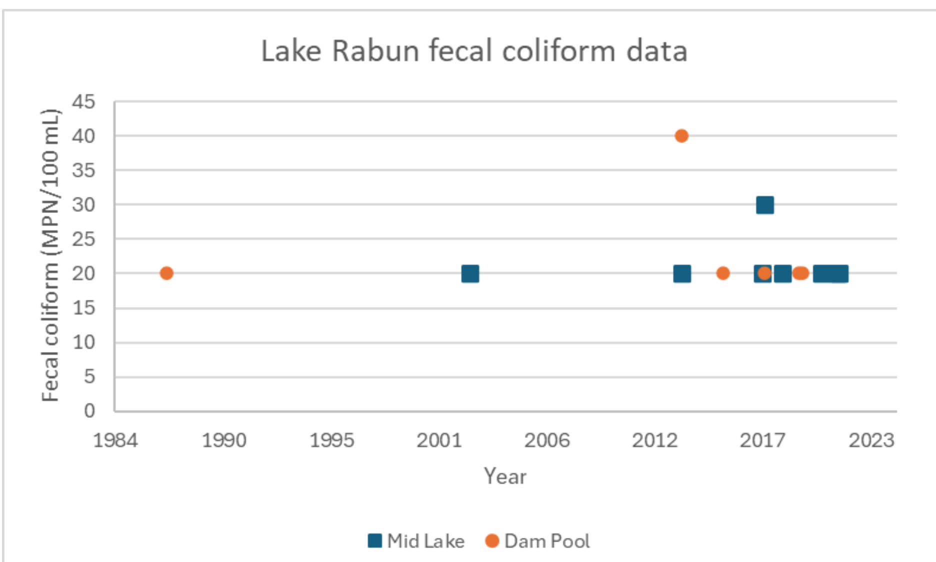


Figure 3-33. Lake Rabun Measured Fecal Coliform Data 1984 – 2021

3.3 Lake Tugalo

Figure 3-34 shows the locations of the Lake Tugalo water quality stations: LK_01_67: u/s Tugalo Lake Rd (aka Bull Sluice Rd.), and LK_01_68: Upstream from Tugaloo Dam. The monitoring sites correspond to the following monitoring location IDs: Mid Lake is LK_01_67 and Dam Pool is LK_01_68. The location names and IDs are used interchangeably in the following figures.

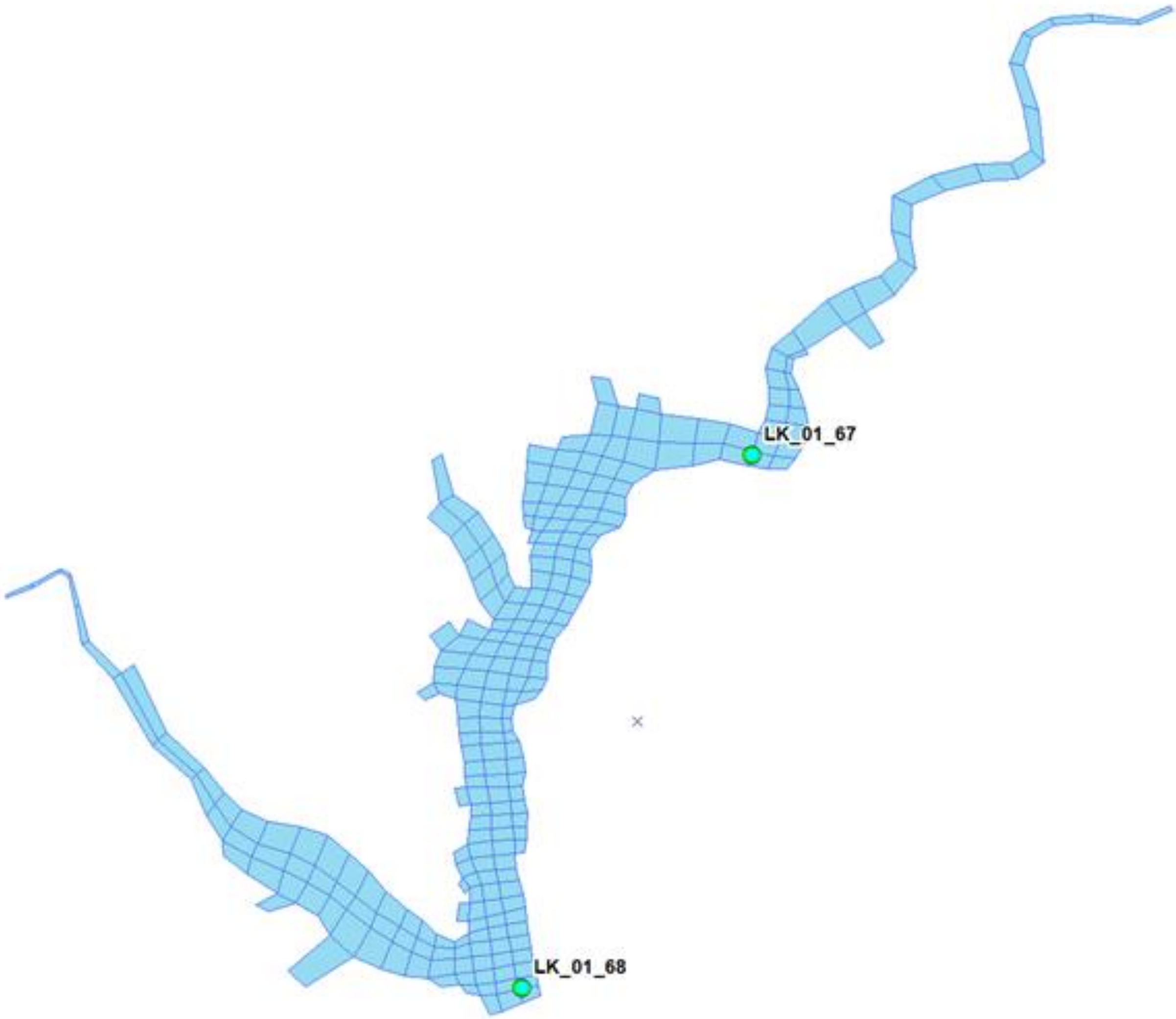


Figure 3-34. Lake Tugalo Monitoring Stations

Figure 3-35 shows measured chlorophyll *a* data from 2002 to 2022 at both stations. This figure shows chlorophyll *a* levels in the lake vary throughout the growing season and year to year.

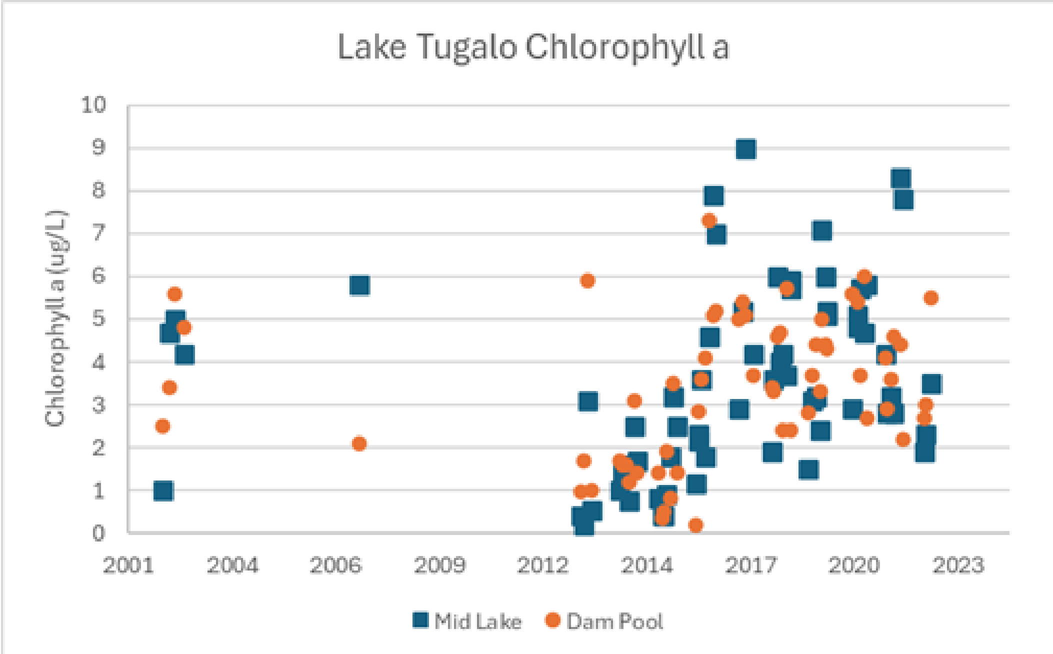


Figure 3-35. Lake Tugalo Measured Chlorophyll a Data 2002 – 2022

Figures 3-36 and 3-37 present the chlorophyll *a* measured at each monitoring station compared to growing season averages for the years 2013 to 2022, along with the proposed criteria. Some of the measured data are slightly above the proposed criteria, whereas the growing season averages are slightly below the proposed criteria.

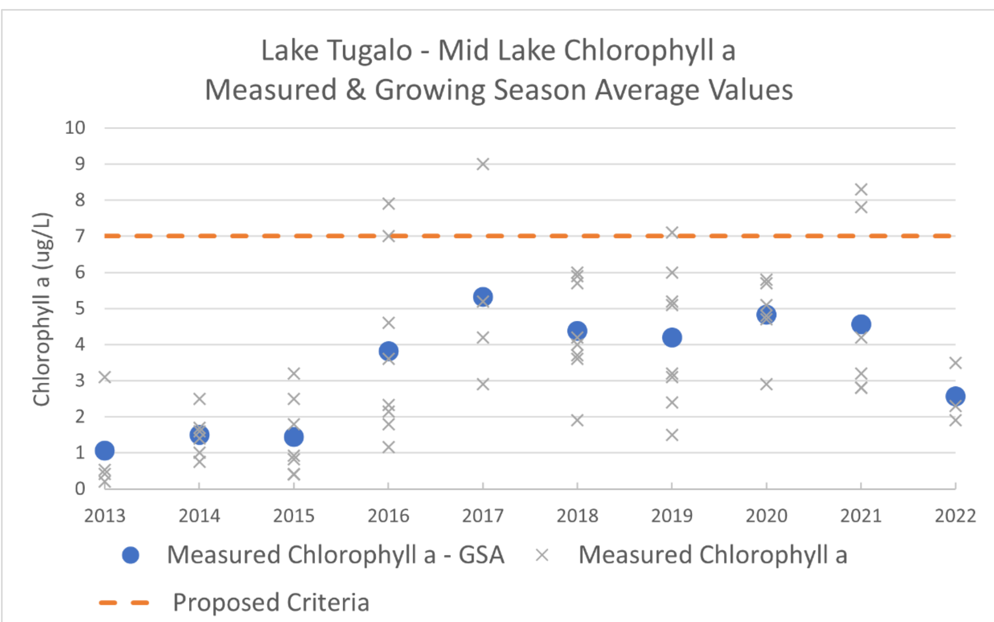


Figure 3-36. Measured Chlorophyll a, Growing Season Averages, and Proposed Criteria at Lake Tugalo - Mid Lake

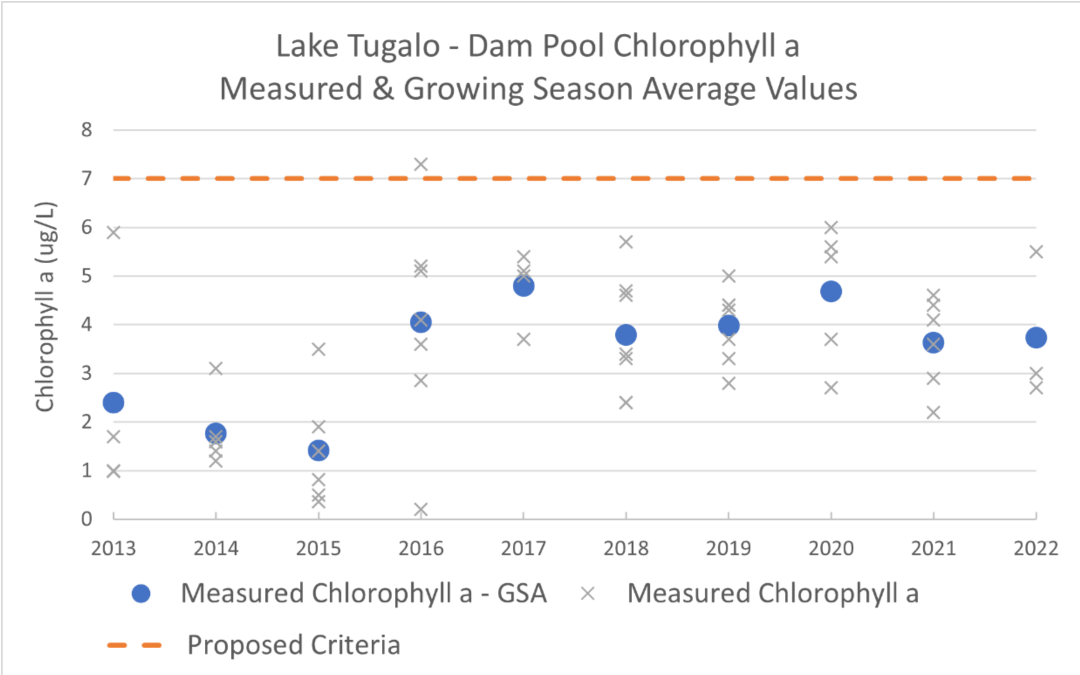


Figure 3-37. Measured Chlorophyll a, Growing Season Averages, and Proposed Criteria at Lake Tugalo - Dam Pool

Figure 3-38 shows measured total nitrogen data from 1984 to 2022 at the Dam Pool monitoring station and from 2002 to 2022 at the Mid Lake monitoring station.

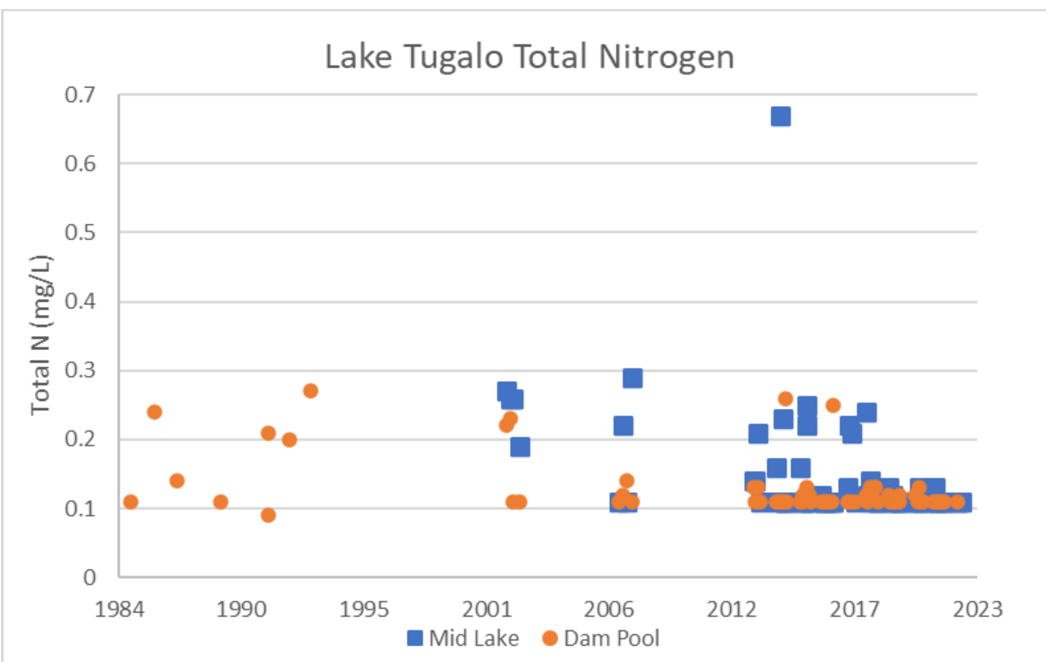


Figure 3-38. Lake Tugalo Measured Total Nitrogen Data 1984 – 2022

Figure 3-39 shows measured total phosphorus data from 1984 to 2022 at the Dam Pool and from 2002 to 2022 at Mid Lake. It appears that the total nitrogen levels have remained in a similar range over time, while total phosphorus levels have seen a significant decrease since the 1980s and 1990s.

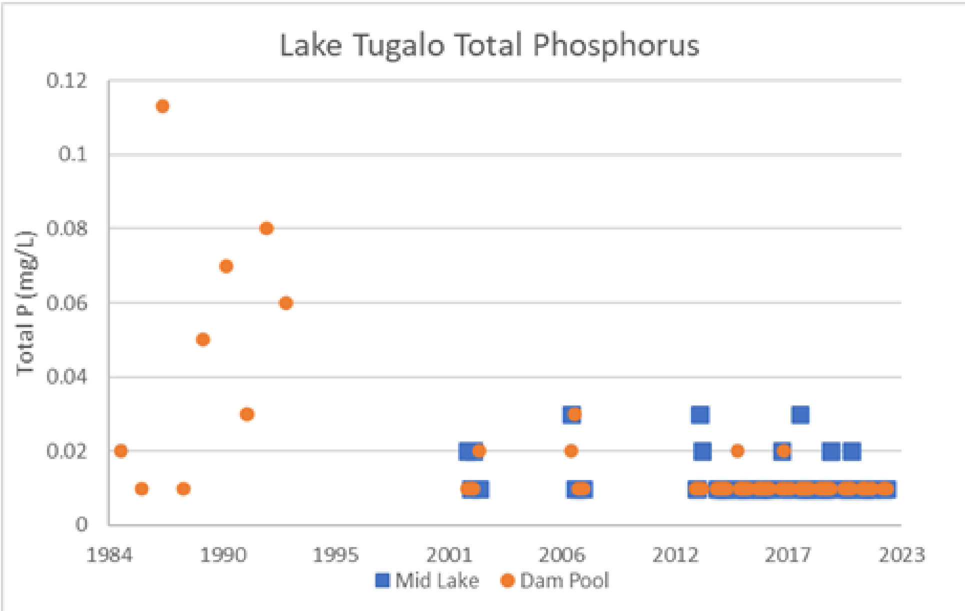


Figure 3-39. Lake Tugalo Measured Total Phosphorus Data 1984 – 2022

Figure 3-40 shows measured pH data from 1980 to 2022 at both stations. This plot shows that most of the time the surface pH ranges between 6.0 and 8.5.

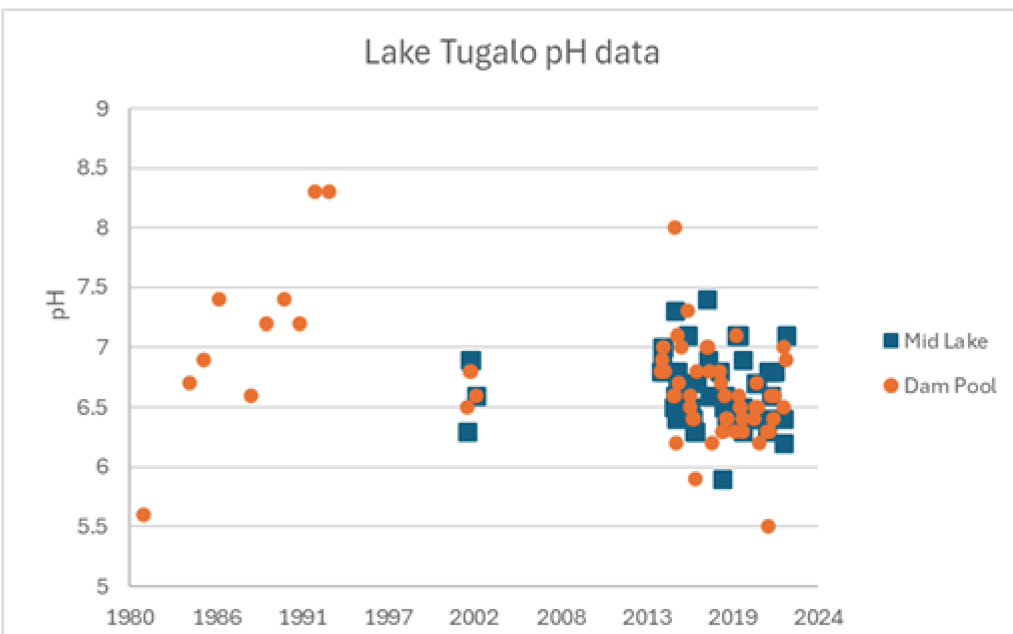


Figure 3-40. Lake Tugalo Measured pH Data 1980 – 2022

Figures 3-41 and 3-42 present the monthly pH profiles at the Lake Tugalo Mid Lake and Dam Pool monitoring stations respectively, from April through October. Each line represents a different year. The pH is typically higher at the surface and decreases with depth. At both monitoring stations, May is the month with the most varied pH levels.

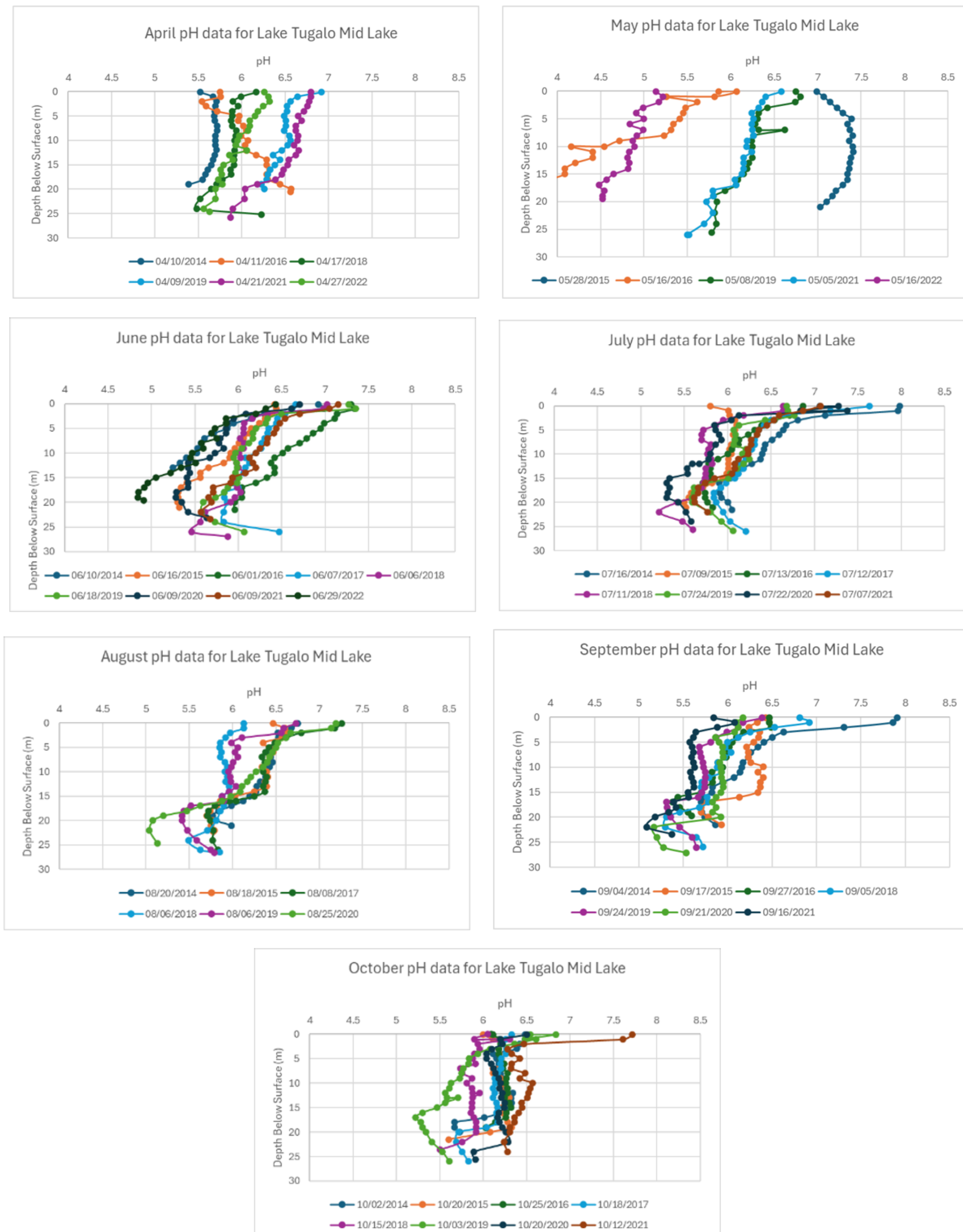


Figure 3-41. Lake Tugalo pH Profile Data at Mid Lake 2014 – 2022

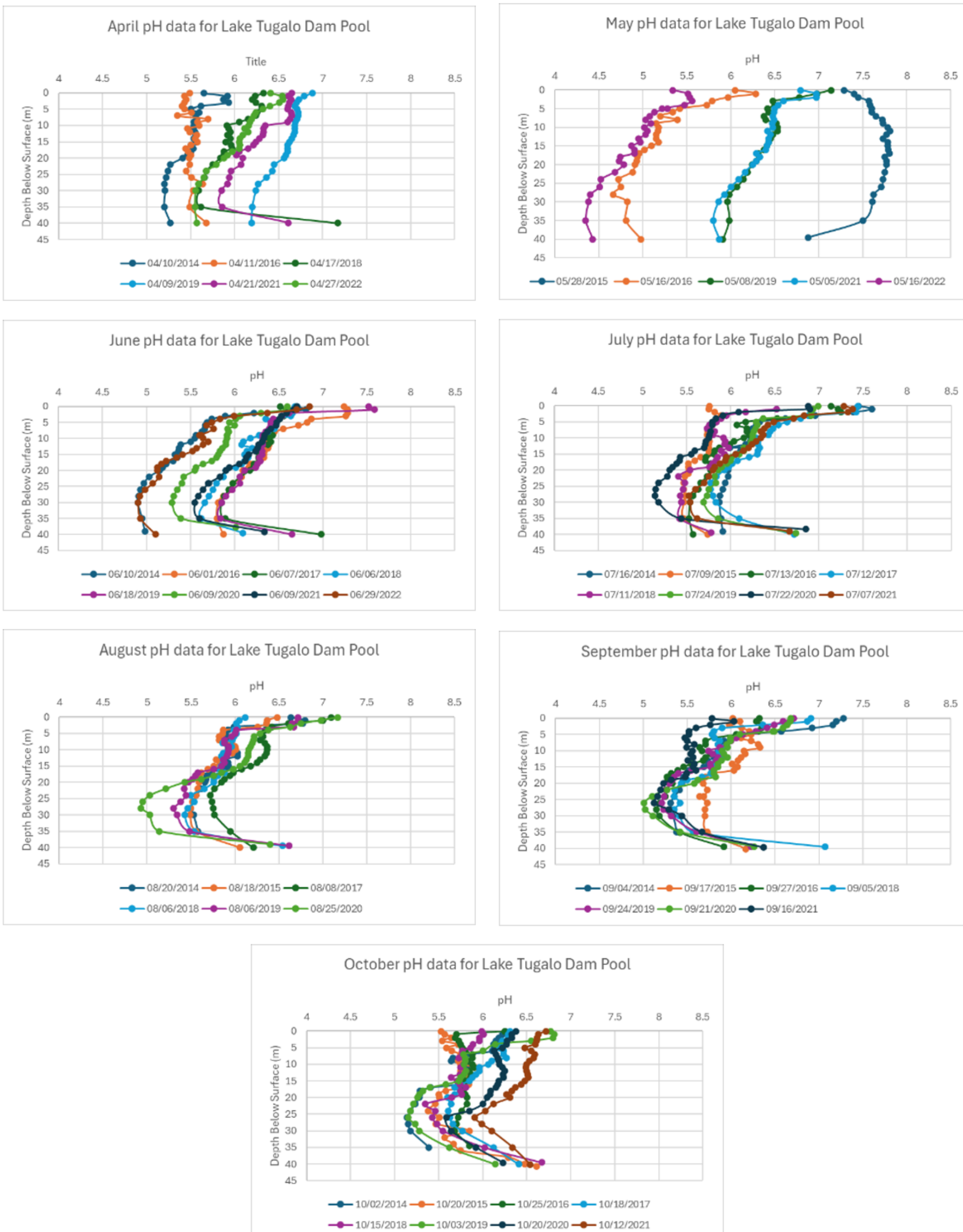


Figure 3-42. Lake Tugalo pH Profile Data at Dam Pool 2002 and 2014 – 2022

Figures 3-43 and 3-44 show the temperature profile data measured in Lake Tugalo at the Mid Lake and Dam Pool monitoring stations, respectively. Each line represents a different year. The temperature criteria of 90 deg F (32.2 deg C) was not exceeded, indicating that the lake is supporting its designated uses. Lake Tugalo has a strong thermocline which is between 15 and 20 meters.

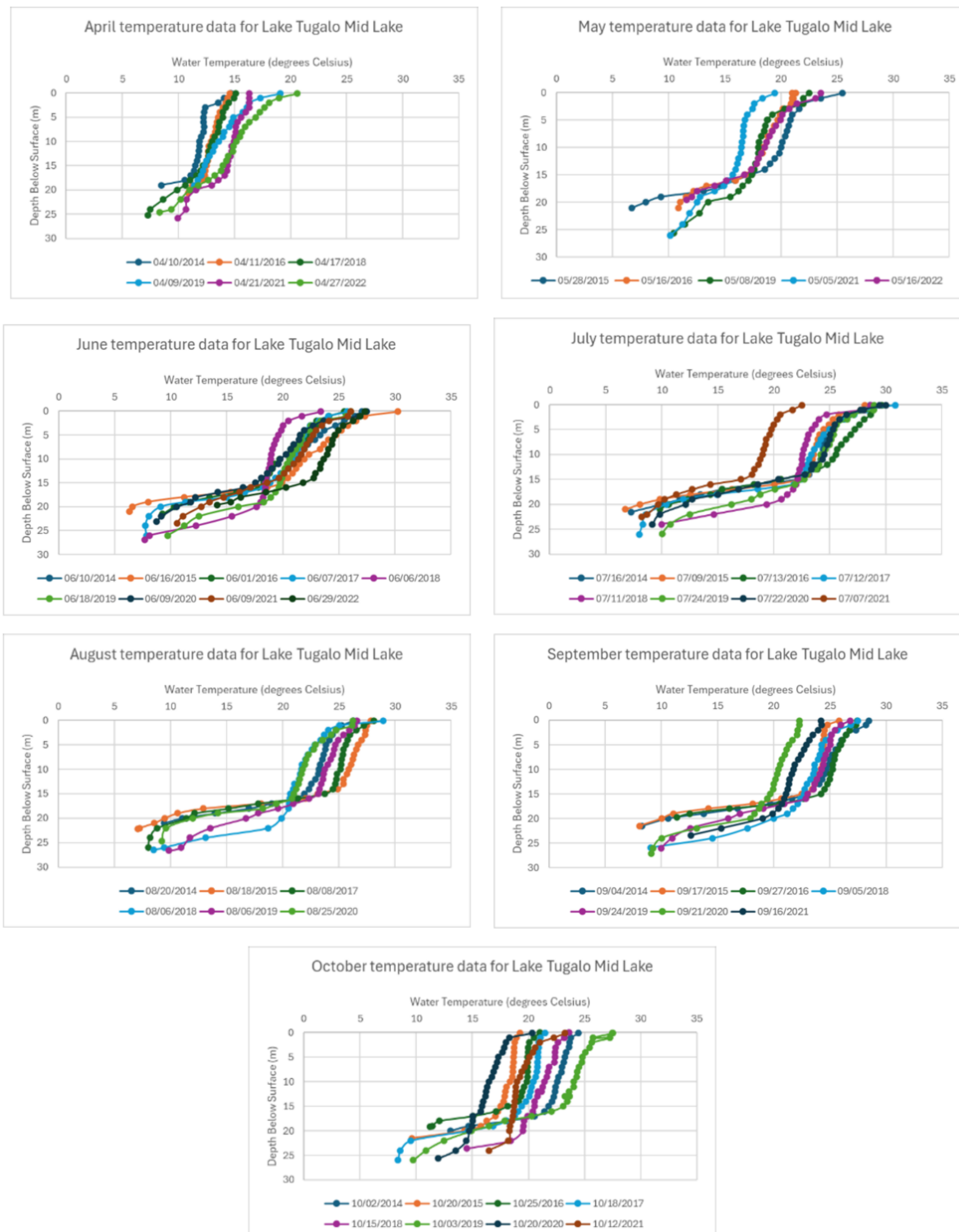


Figure 3-43.Lake Tugalo Temperature Profile Data at Mid Lake 2014 – 2022

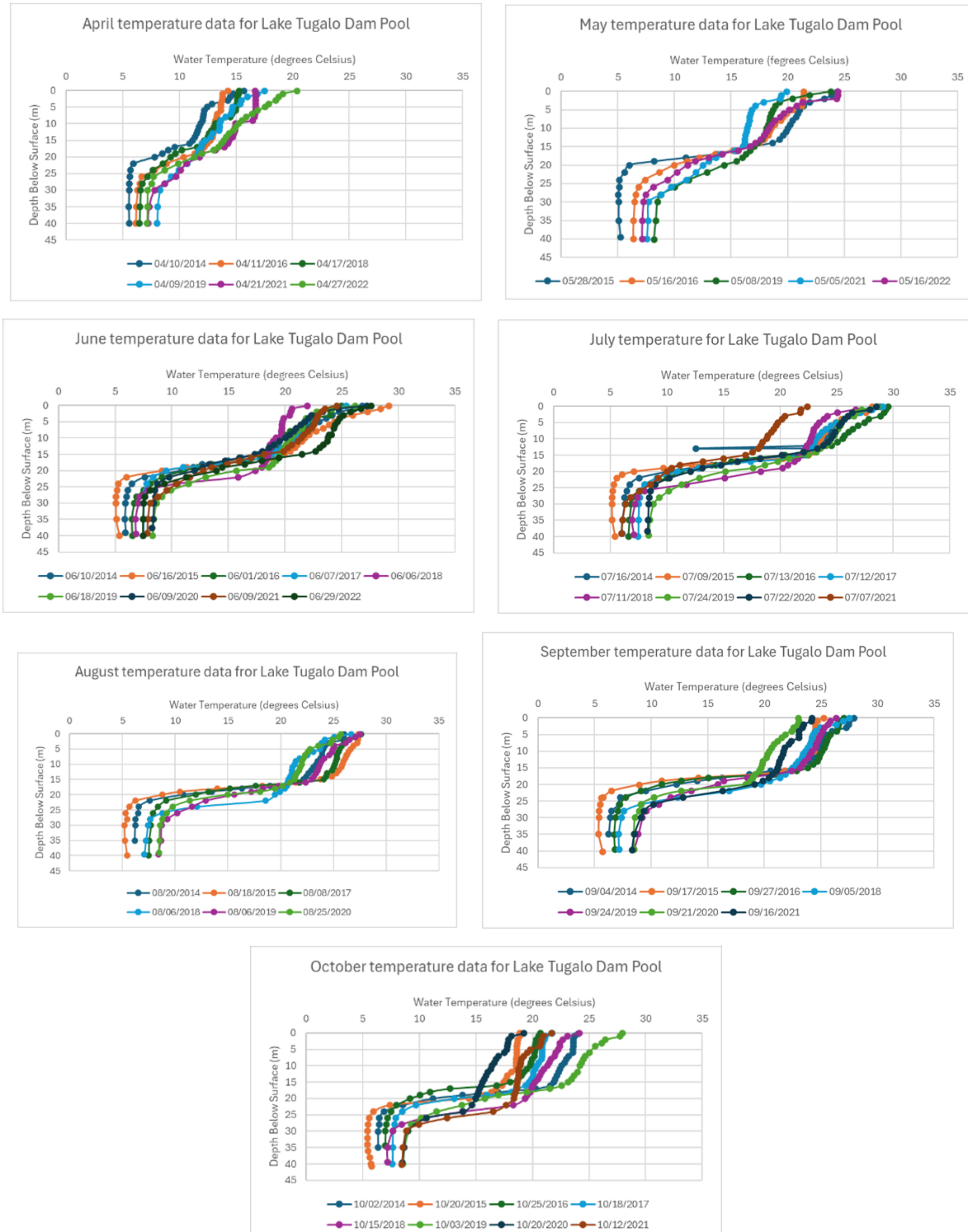


Figure 3-44. Lake Tugalo Temperature Profile Data at Dam Pool 2014 – 2022

Figures 3-45 and 3-46 display dissolved oxygen (DO) depth profile data for the Mid Lake and Dam Pool monitoring locations, respectively. Each line represents a different year. The dissolved oxygen tends to follow the thermocline. At the 1 meter depth, DO concentrations meet the water quality criteria.

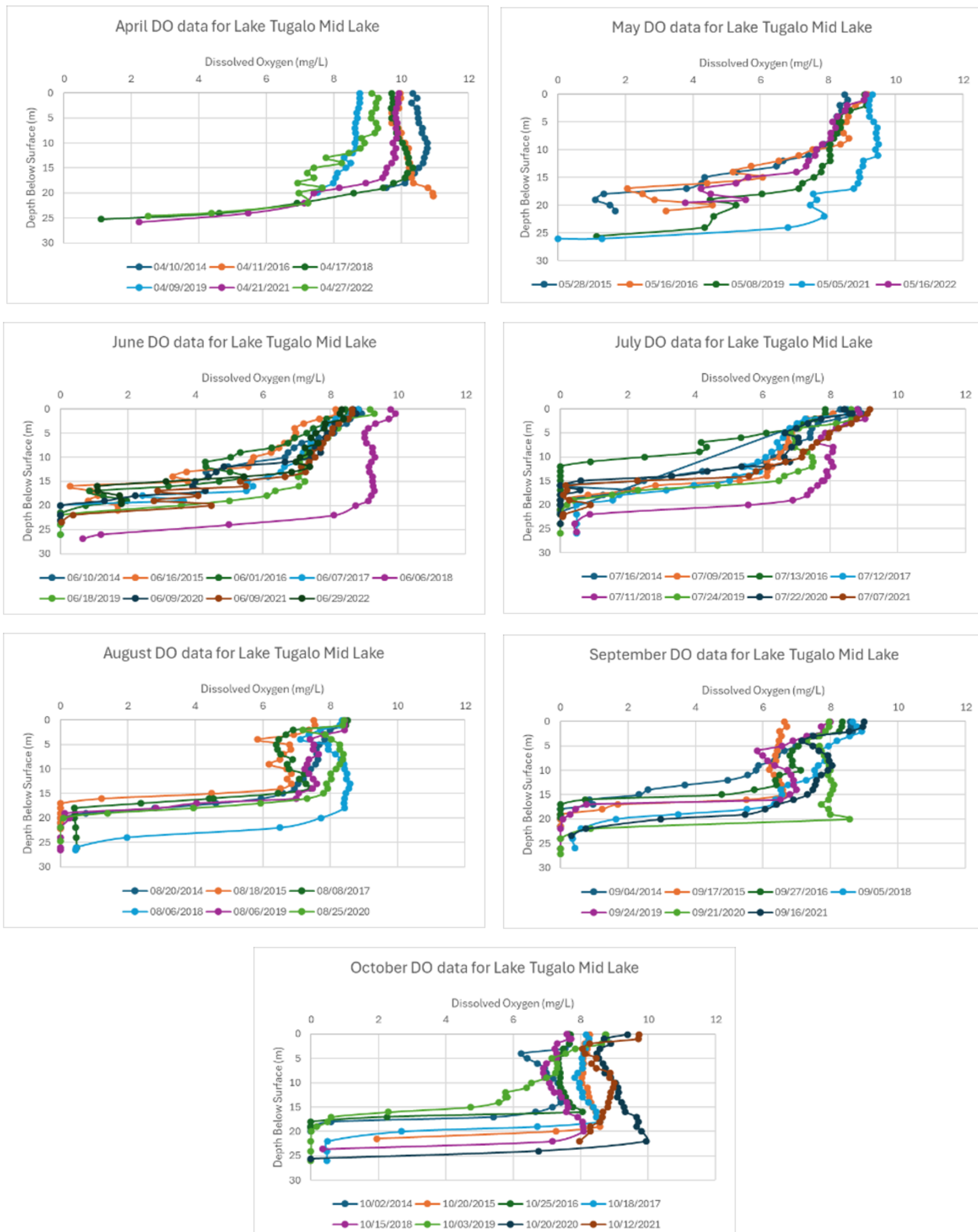


Figure 3-45. Lake Tugalo Dissolved Oxygen Profile Data at Mid Lake 2014 – 2022

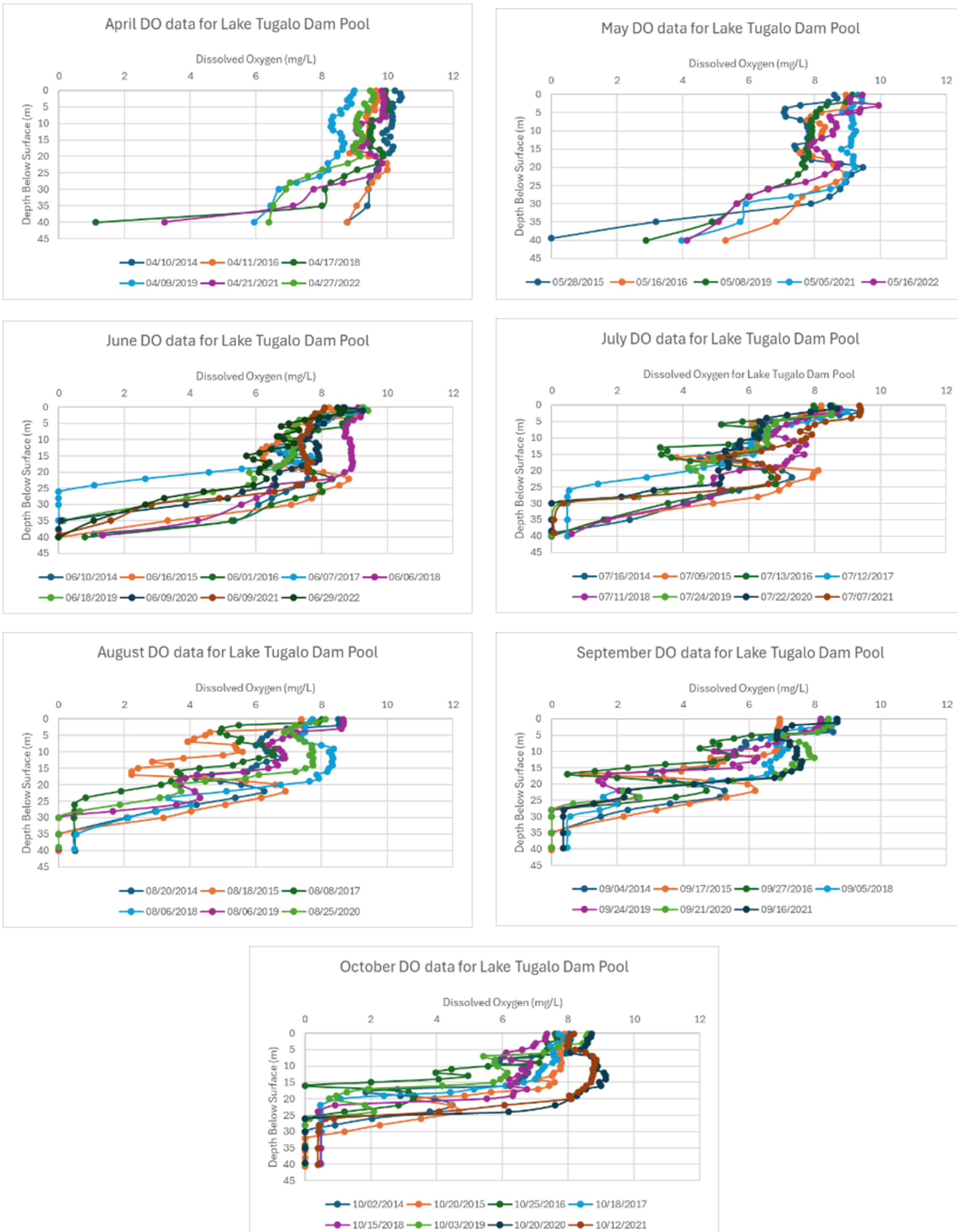


Figure 3-46. Lake Tugalo Dissolved Oxygen Profile Data at Dam Pool 2014 – 2022

Figure 3-47 shows DO data measured at Lake Tugalo at a depth of one meter below the water surface from 2002 to 2022. The instantaneous DO at the one-meter depth meets the DO water quality criteria of a daily average of 5 mg/L and no less than 4.0 mg/L at all times, therefore the lake is supporting its designated uses.

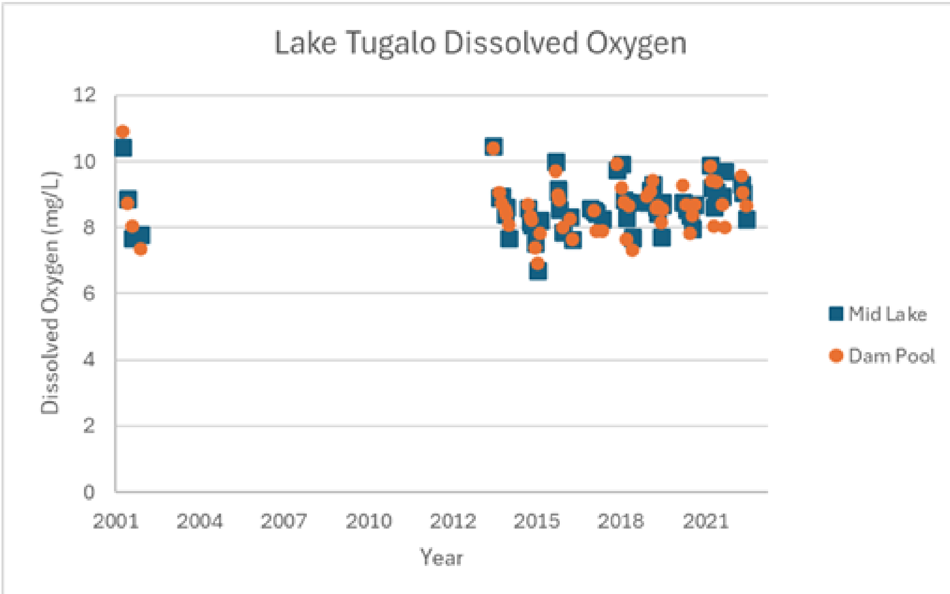


Figure 3-47. Lake Tugalo Measured Dissolved Oxygen Data 2002 – 2022

Figure 3-48 is a plot of the E. coli levels measured in Lake Tugalo above the detection limit. These data are from grab samples collected at the surface of the lake. Thirty-seven samples were collected at each monitoring station from 2015 to May 2022. Both stations had twenty-six samples that detected no E. coli, with a reporting limit of 20 MPN/100 mL. Figure 3-48 displays only samples where E. coli were detected. Only four of the single monthly samples exceeded the Statistical Threshold Value of 410 counts/100 mL or the 30-day geometric mean E. coli criteria (126 counts/100 mL) that supports primary recreation. This indicates that Lake Tugalo is meeting its designated uses.

Figure 3-49 is a plot of fecal coliform levels measured in Lake Tugalo above the detection limit. These data are from grab samples collected at the surface of the lake. Sixty-two samples were collected at the Mid Lake monitoring station between 2002 and 2021. Forty-two of these samples had no detectable fecal coliform, with a reporting limit of 20 MPN/100 mL. Sixty-seven samples were collected at the Dam Pool station between 1984 and 2021, forty-nine detected no fecal coliform. Figure 3-49 displays only samples in which fecal coliform were detected. Four of these samples exceeded the 30-day geometric mean fecal coliform criteria (200 counts/100 mL) that supported primary recreation prior to the change to E. coli as the bacteria indicator for recreation designated use in 2015. These data indicate that Lake Tugalo has historically met its designated uses.

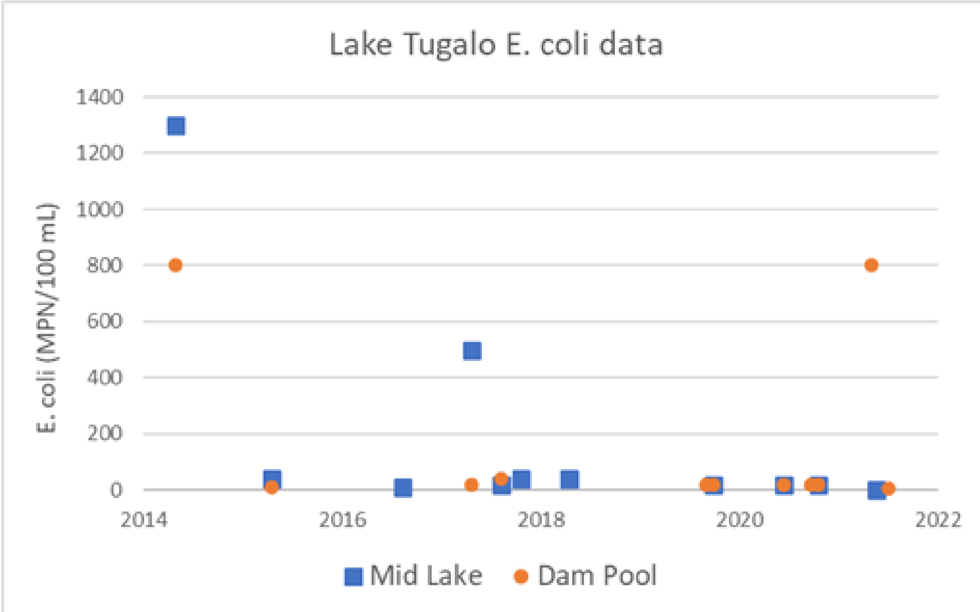


Figure 3-48. Lake Tugalo Measured E. coli Data 2015 – 2022

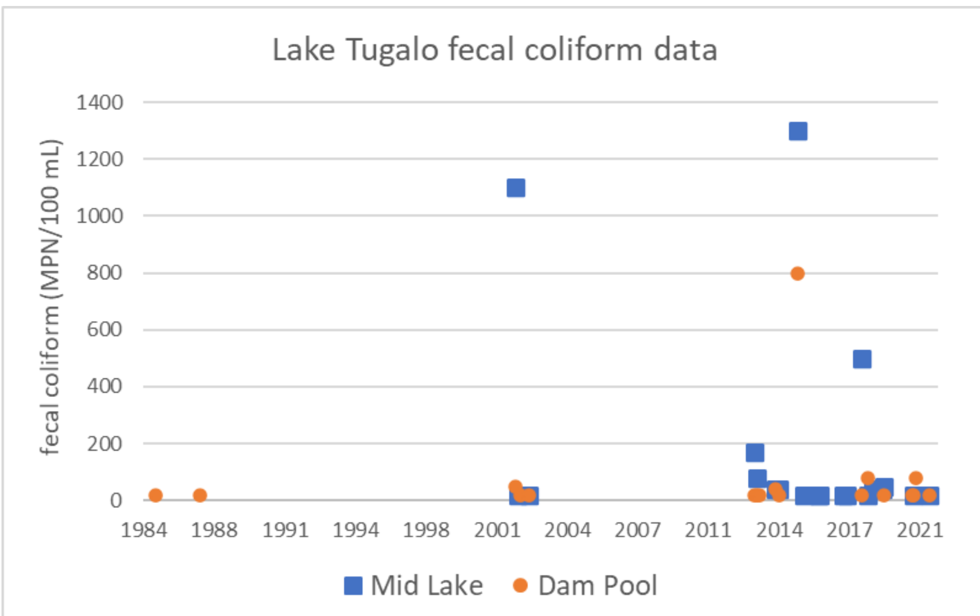


Figure 3-49. Lake Tugalo Measured Fecal Coliform Data 1984 – 2021

4.0 WATER QUALITY MODELING

The process of developing the numeric chlorophyll *a* and nutrient criteria for Lakes Burton, Rabun, and Tugalo includes developing computer models for the lakes and their watersheds. The watershed model of the Upper Savannah River watershed was developed using the Loading Simulation Program in C++ (LSPC). The LSPC model included a representation of watershed land uses and all major point sources of nutrients within the watershed. The watershed model simulated the effects of surface runoff on both water quality and flow and was calibrated to available data. The results of the LSPC model were used as tributary flow inputs to the lake hydrodynamic and water quality model, which was built with Environmental Fluid Dynamics Code (EFDC).

The EFDC model was used to simulate the transport of water into and out of the lake, as well as the fate and transport of nutrients into and out of the lake and the uptake by phytoplankton. The growth and death of phytoplankton is measured through a surrogate parameter called chlorophyll *a*. The EFDC model was calibrated to nutrient and chlorophyll *a* concentrations. Figure 4-1 shows how the two models interact with one another and what outputs each model provides. The computer models used to develop these numeric criteria are described in the following sections.

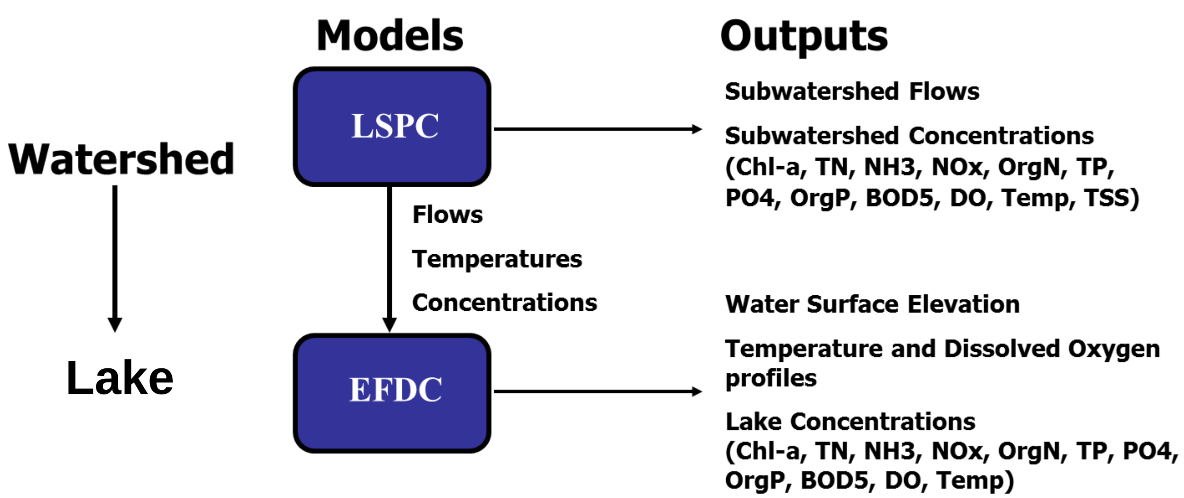


Figure 4-1. Linkage between LSPC and EFDC

Historical flow data collected at USGS stations located on the Tallulah River at Plum Orchard Road and the Chattooga River at US Hwy 76 were used to calibrate and validate the LSPC watershed hydrology model. These gages had a complete period of record for the period from January 1, 1998, through December 31, 2020. There were limited water quality data available to calibrate the LSPC models.

Deterministic time variable models predict conditions within the computational domain of the model based upon perturbations within the model grid caused by outside forcing functions. The forcing functions required by the hydrodynamic lake models included:

- Inflows and outflows,
- Water temperature assignments to the inflows, and
- Meteorological conditions (wind, solar radiation, etc.)

For calibration purposes, time dependent or constant values for each of these parameters must be applied at the appropriate boundaries for the entire model simulation period. These values were applied at all the boundaries within the system including:

- Dam releases, and
- Lateral tributaries inflows

The simulation period for the hydrodynamic model was over a 19-year period, from January 1, 2001, through December 31, 2020. This period was chosen because it captures several wet (2009, 2013, 2018, and 2020), dry (2000, 2001, 2006, 2007, 2011, and 2016), and normal years (2003, 2010, and 2017).

The EFDC models for Lakes Burton, Rabun, and Tugalo were set up using the following variables:

- Organic nitrogen
- Ammonia
- Nitrate-Nitrite
- Organic phosphorus
- Orthophosphate
- Algae (2 species)
- Dissolved oxygen
- Organic carbon
- Silica

The EFDC grid for Lake Burton covers the entire lake and includes the Tallulah River just downstream of its confluence with Plum Orchard Creek. The grid includes Dicks Creek, Moccasin Creek, Wildcat Creek, Cherokee Creek, Murray Cove, and Timpson Creek. The EFDC grid for Lake Rabun covers the entire lake and starts at the base of the Nacoochee Dam, just downstream from Lake Seed a run of the river reservoir and ends at the Mathis Dam. The EFDC grid for Lake Tugalo starts just downstream of Tallulah Falls on the Tallulah River and at the confluence of Opossum Creek with the Chattooga River and ends downstream at the Tugalo Dam.

The models were run for calendar years 2001 through 2020. During 2004, and 2013 to present, water quality data were collected in the lakes and these data were used to calibrate the model. The data examined included chlorophyll *a*, nitrogen components, phosphorus components, dissolved oxygen profiles, and water temperature profiles. The calibration models were run using input data for this period, including boundary conditions and meteorological data.

The models were used to assess and develop the numeric nutrient and chlorophyll *a* criteria for Lakes Burton, Rabun, and Tugalo. The complex dynamics simulated by the models demonstrated the critical conditions for nutrient uptake and the corresponding algal growth. The critical conditions include:

- Meteorological conditions
- Available sunlight
- Watershed flows
- Retention time in the lakes
- High water temperatures
- Watershed nutrient loads

The most critical period for excess algal growth appears to be the high-flow years when excess nutrients have been delivered to the system. The high-flow critical conditions are assumed to represent the most critical design conditions thereby providing year-round protection of water quality. During these years, the rainfall is high, sunlight can be unlimited, and nutrient fluxes may be high. The large amounts of nutrients delivered during these high-flow sunny periods can cause algae to bloom and measured chlorophyll *a* can exceed the numeric standards. High flows occurred in 2003, 2005, and 2009-2010.

Drought conditions were experienced a couple of times during the period from 2001 through 2020. This simulation period exhibited a wide variety of average flow conditions, which included low flow drought conditions in 2001-2002, 2006-2007, 2011, and 2016. Normal flows occurred in 2003, 2010, and 2017. Periods of dry weather occurred followed by heavy rains, which caused some instances of high measured nutrient values (2018).

4.1 Description of Scenarios

Five scenarios were run using the models to explain the sources and contributions of chlorophyll *a* levels observed, and for use in developing the chlorophyll *a* and nutrient criteria. In each scenario, simulated watershed flows and water quality loads from the LSPC models were used as inputs into the EFDC models. In each lake EFDC model, outputs for calendar years 2001 through 2020 were evaluated at two monitoring locations as described in Chapter 3 – Water Quality Data. Results for chlorophyll *a* were evaluated based on growing season averages (April 1 through October 31). A short description of each scenario is presented below.

4.1.1 Calibration (Scenario 1A)

Scenario 1A was performed using the Lake Burton, Lake Rabun, and Lake Tugalo watersheds hydrology and water quality model (LSPC) and the calibrated Lake Burton, Lake Rabun, and Lake Tugalo models (EFDC). The LSPC models were run using daily rainfall data and monthly flow and water quality data from point source discharges given in the monthly Discharge Monitoring Reports (DMRs). The EFDC models were run using monthly water withdrawals, as well as monthly flow and water quality data from point source discharges given in the monthly Discharge Monitoring Reports (DMRs). If no data were available for the point source discharges, values were input at the permitted limits. If no permit limit existed values were used which assumed phosphorus limits using the GA EPD Phosphorus Strategy, found online at https://epd.georgia.gov/document/publication/signed-p-strategypdf/download. This scenario represents current conditions that are currently meeting designated uses.

4.1.2 All Forested (Scenario 1B)

Scenario 1B was an all-forested scenario. In this scenario, point source discharges, water withdrawals, and septic tanks were removed, and all land use was converted to forest. This model was relevant for our derivation of chlorophyll *a* criteria because it confirmed that some locations naturally have higher chlorophyll *a* concentrations without the influence of land use and point sources.

4.1.3 Nutrient Permitting Strategy (Scenario 1C)

Scenario 1C had point source discharges input at GA EPD Nutrient Strategy phosphorus levels. Facilities with a permitted flow $\geq$ 1 MGD were given a total phosphorus level of 1.0 mg/L, and facilities with a permitted flow < 1 MGD were given a total phosphorus load of 8.34 lbs/day or a total phosphorus level of 5 mg/L, whichever is smaller.

4.1.4 2060 Permitted Flows Maintaining Loads and 2060 Land Use (Scenario 1D)

Scenario 1D was a 2060 Point Source and 2060 forecasted Land Use scenario. Point source discharges were set at the 2060 flows forecasted in the State Water Plan. However, the total phosphorus load was the same as in Scenario 1C.

4.1.5 Increased Permitted Nutrient Loads (Scenario 1E)

Scenario 1E consisted of two model runs; one where the point source total phosphorus load used in Lake Tugalo Scenario 1C was increased by an order of magnitude and the second where the point source total nitrogen load in Lake Tugalo was increased by an order of magnitude. These model runs were done to determine the sensitivity of the modeled chlorophyll *a* levels to the nutrient levels.

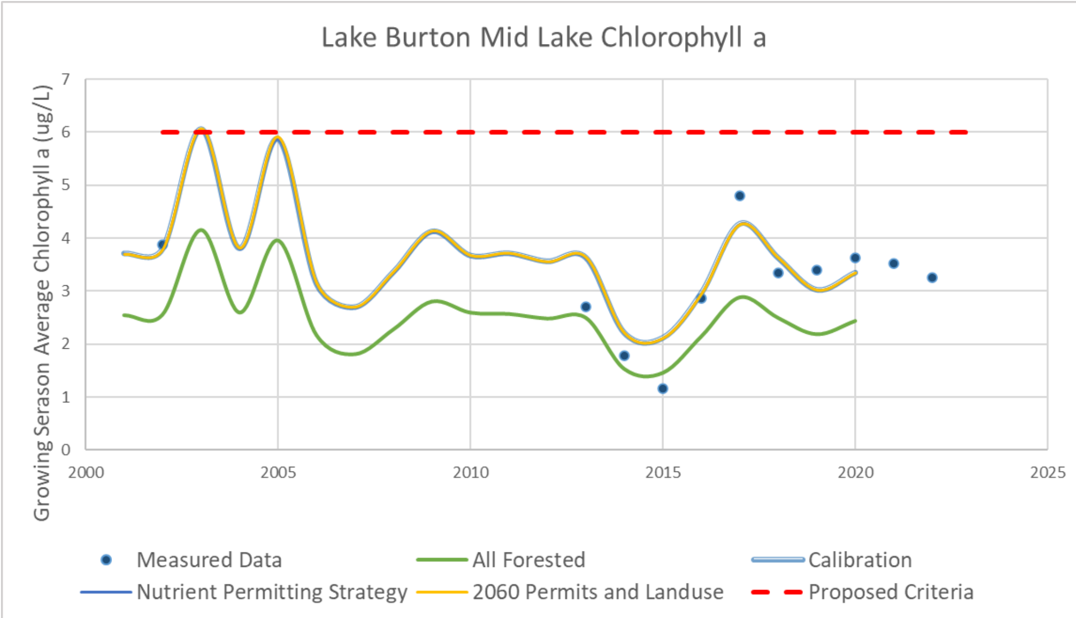
4.2. Chlorophyll *a* Results

Table 4-1 provides the maximum growing season average chlorophyll *a* levels predicted during the simulation period for each scenario, at the monitoring stations on both lakes, compared to the proposed chlorophyll *a* criteria. Figures 4-2, 4-3, and 4-4 show the resulting growing season average chlorophyll *a* levels for each of Scenario 1A-1D. The results of the Scenario 1E model run indicate that Lake Tugalo is phosphorus limited as shown in Figures 4-5. The chlorophyll *a* levels were not affected by changing the permitted total nitrogen loads by an order of magnitude but increased when the permitted total phosphorus loads were increased by an order of magnitude.

Table 4-1. Lake Maximum Growing Season Average Chlorophyll a Concentrations for Each Scenario Compared to the Proposed Growing Season Average Chlorophyll a Criteria

<table>
<tr><th rowspan="2">Lake</th><th rowspan="2">Monitoring Station</th><th colspan="6">Scenario</th><th rowspan="2">Proposed Criteria (ug/L)</th></tr>
<tr><th>1A</th><th>1B</th><th>1C</th><th>1D</th><th>1E TN</th><th>1E TP</th></tr>
<tr><td rowspan="2">Lake Burton</td><td>1/4 mile South of Burton Island (aka Tallulah River)</td><td>6.06</td><td>4.16</td><td>6.06</td><td>6.07</td><td colspan="2" rowspan="4">1E scenario only evaluated for Lake Tugalo</td><td>6</td></tr>
<tr><td>Dampool (aka Tallulah River - Upstream from Lake Burton Dam)</td><td>5.34</td><td>3.59</td><td>5.34</td><td>5.34</td><td>6</td></tr>
<tr><td rowspan="2">Lake Rabun</td><td>Approx. 4.5 mi u/s Dam (Mid Lake)</td><td>5.03</td><td>3.77</td><td>5.09</td><td>5.43</td><td>6</td></tr>
<tr><td>Dampool (aka Tallulah River - Upstream From Mathis Dam)</td><td>4.72</td><td>3.34</td><td>4.78</td><td>5.13</td><td>6</td></tr>
<tr><td rowspan="2">Lake Tugalo</td><td>Upstream of Tugalo Lake Rd (aka Bull Sluice Rd.)</td><td>4.15</td><td>3.70</td><td>4.52</td><td>4.33</td><td>4.57</td><td>4.87</td><td>7</td></tr>
<tr><td>Upstream from Tugalo Dam</td><td>4.49</td><td>3.52</td><td>5.14</td><td>4.65</td><td>5.28</td><td>5.84</td><td>7</td></tr>
</table>

The Lake Burton, Rabun, Tugalo proposed criteria are slightly above the 2060 Permitted Flows Maintaining Loads and Current Land use. The proposed criteria for all the lakes are close to the historical data and these levels are within the range of typical chlorophyll *a* concentrations found in Blue Ridge Mountain lakes. The “All Forested” run confirms that the proposed criteria are reasonable since the relative proportions are similar. To meet the proposed chlorophyll *a* criteria, all NPDES permits will require total phosphorus limits. The criteria have been established with a margin of safety to allow for the variability of the measured data.



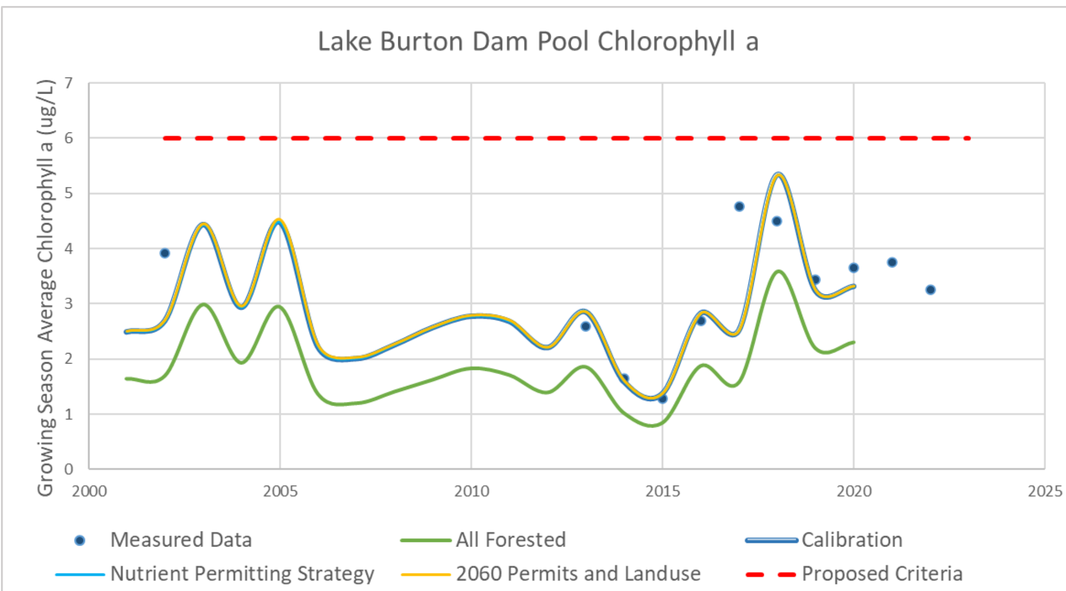
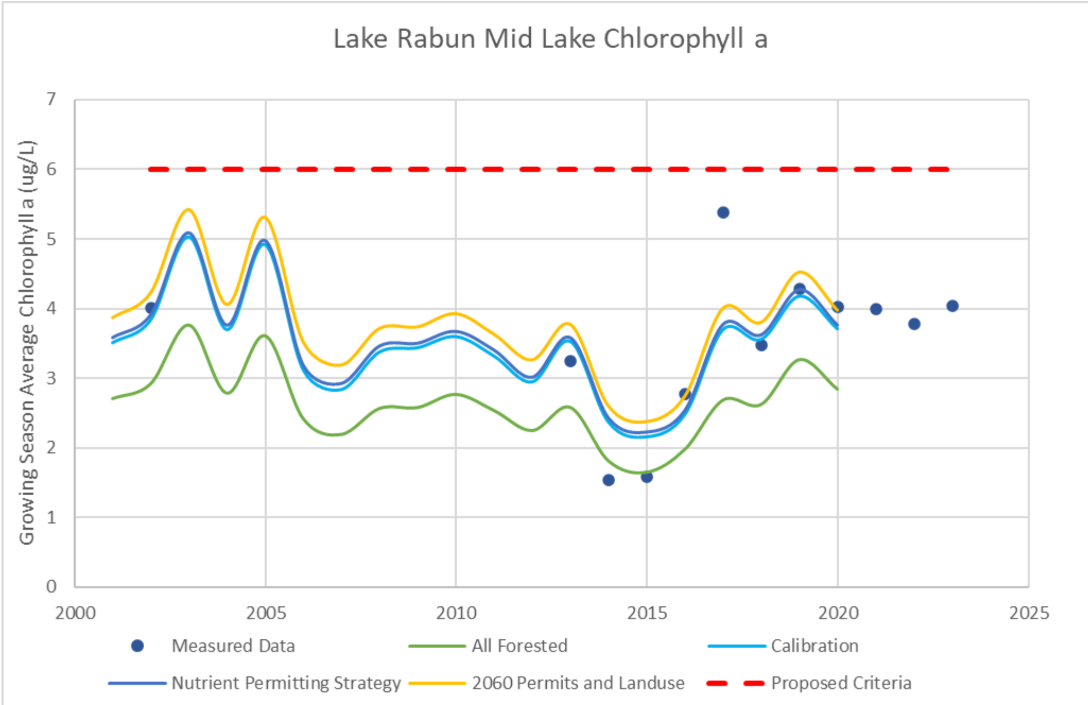


Figure 4-2. Lake Burton Growing Season Average Chlorophyll a Levels from four Model Scenarios compared to the Proposed Criteria and Measured Values



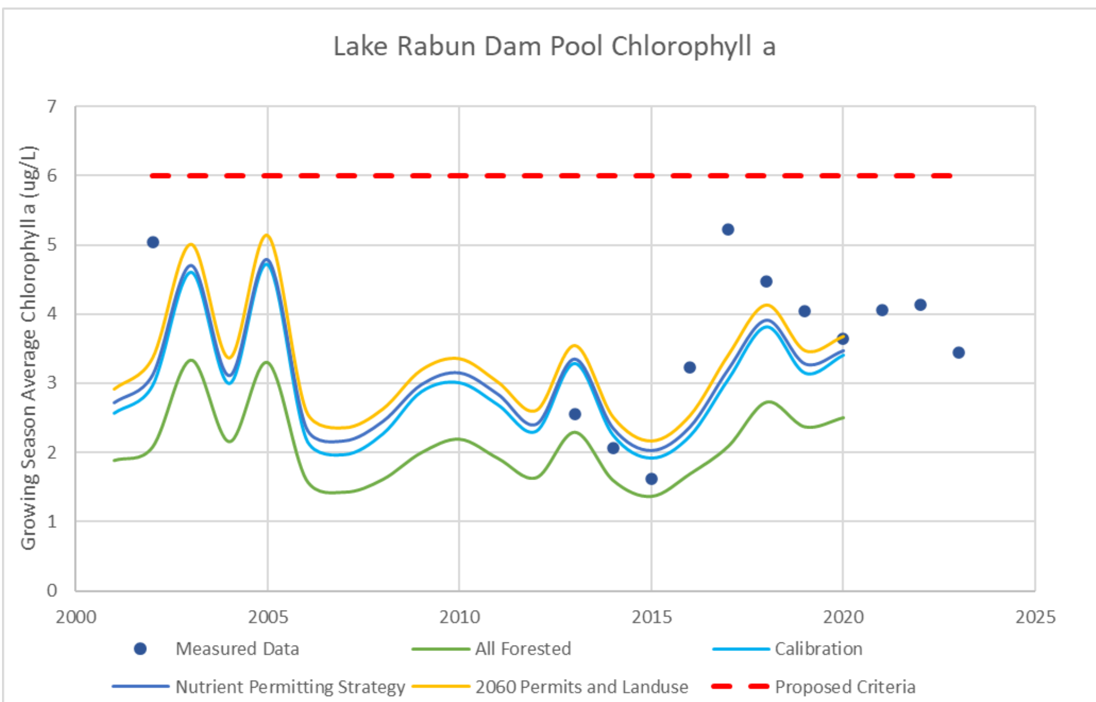
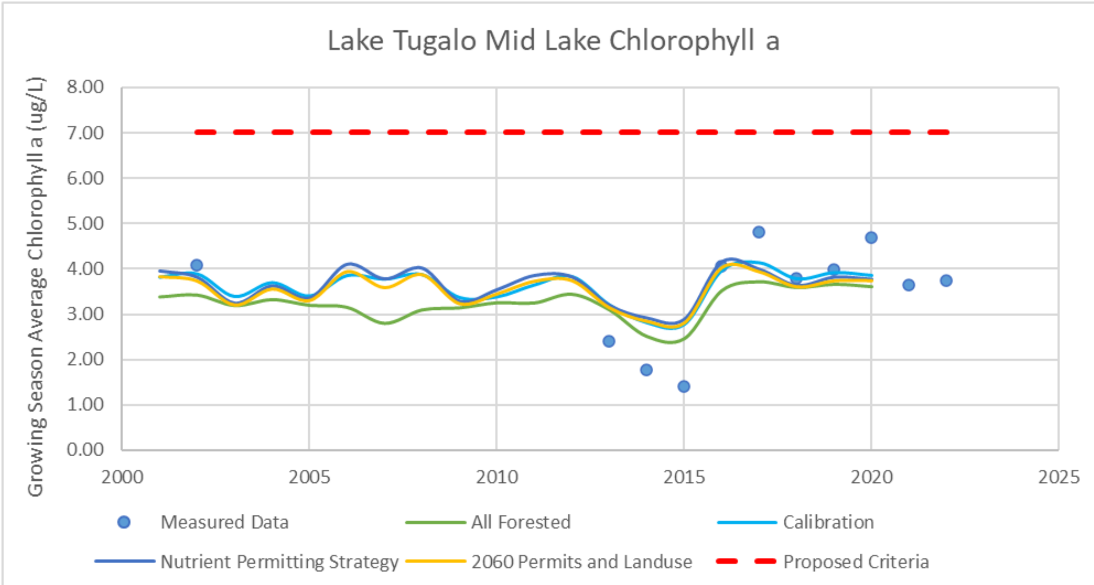


Figure 4-3. Lake Rabun Growing Season Average Chlorophyll a Levels from four Model Scenarios compared to the Proposed Criteria and Measured Values



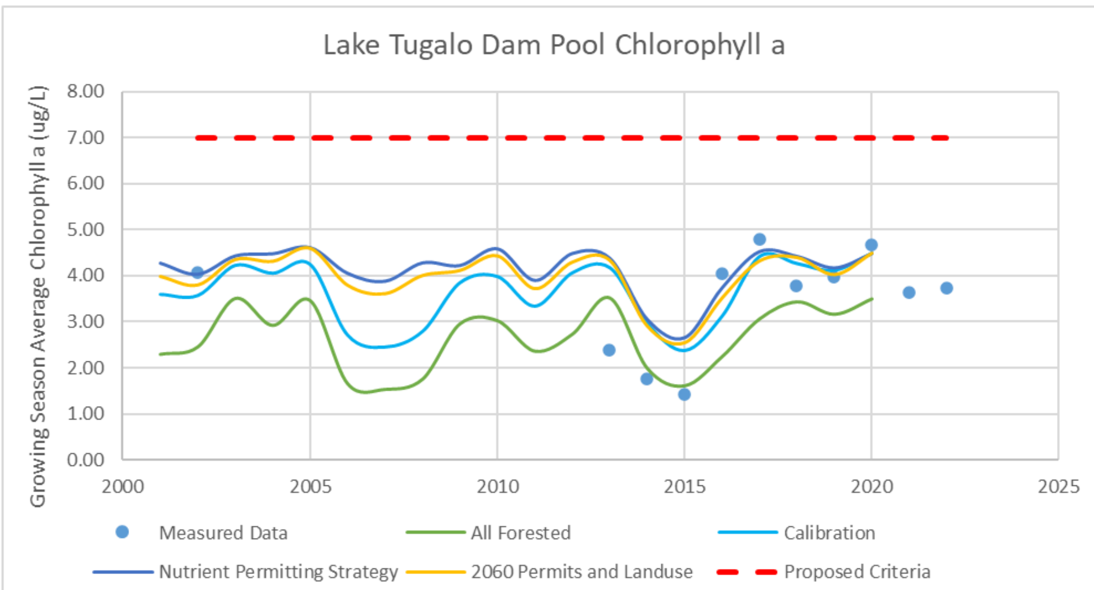
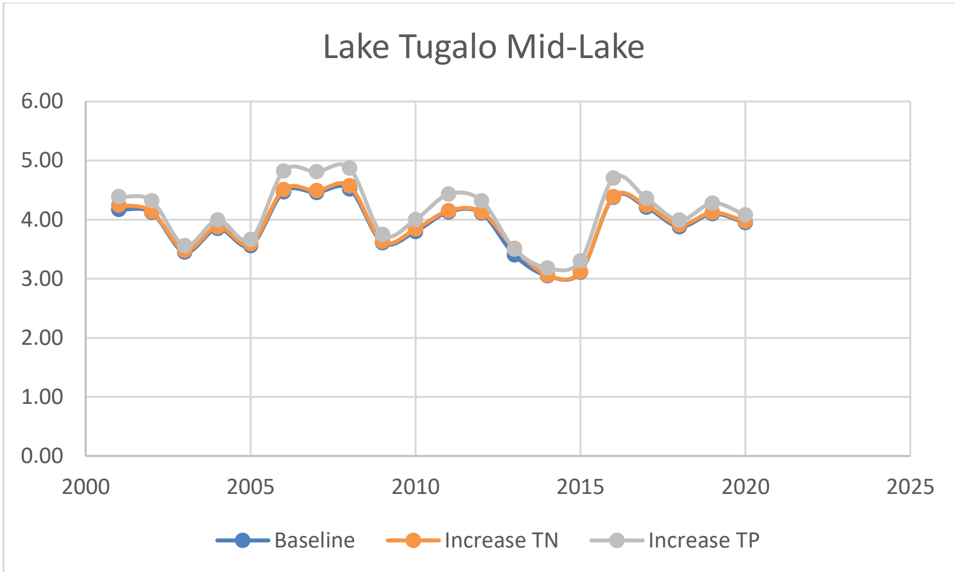


Figure 4-4. Lake Tugalo Growing Season Average Chlorophyll a Levels from four Model Scenarios compared to the Proposed Criteria and Measured Values

Figure 4-5 shows the effects of increasing the point source nutrient loads in the Lake Tugalo watershed by an order of magnitude on the chlorophyll results (Scenario 1E). These model runs show that the lake is phosphorus limited.



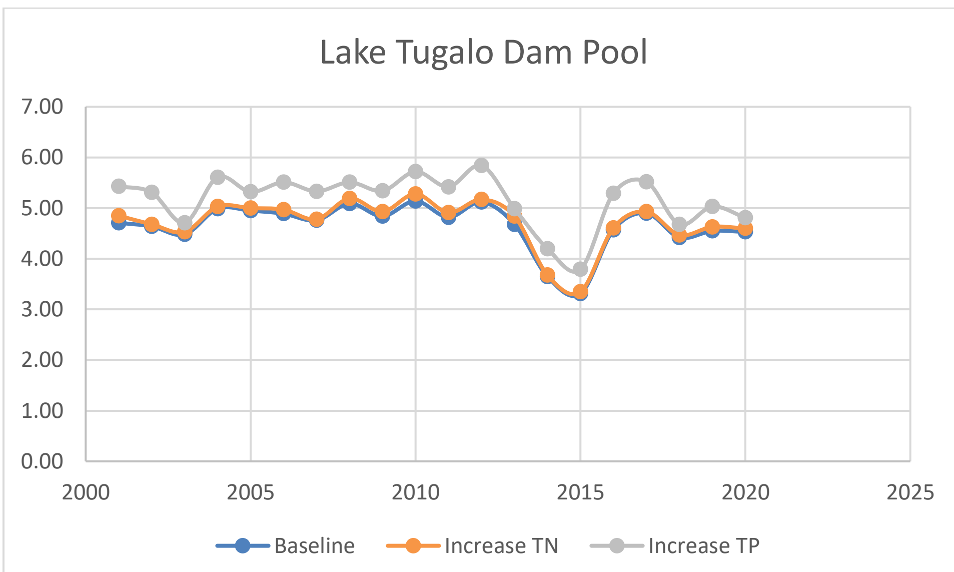
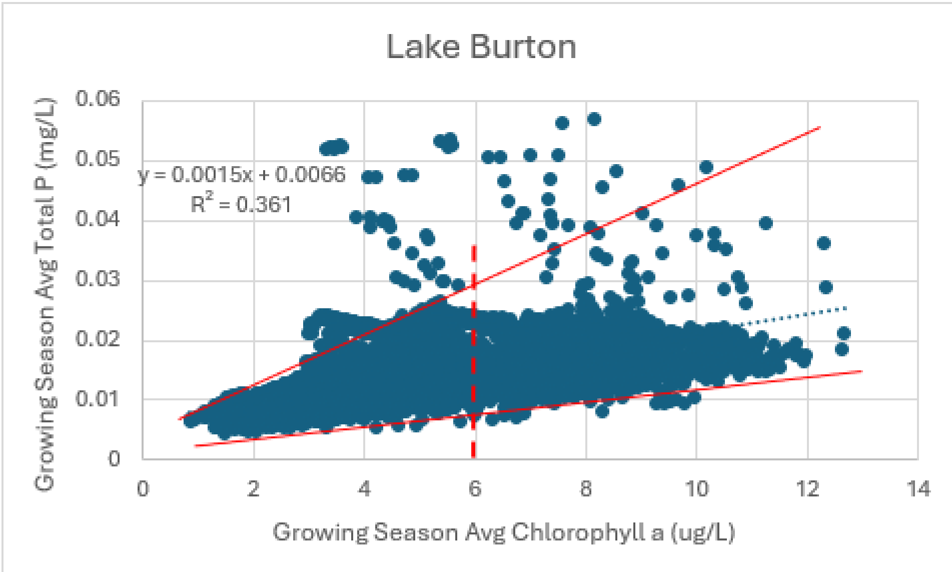


Figure 4-5. Effect of Nutrient Increases on Lake Tugalo Chlorophyll a Levels

4.3 Causal Response Relationship Between Total Nitrogen and Total Phosphorus and Chlorophyll

To determine the causal response relationship between nutrient and chlorophyll a, the modeled growing season average nutrient levels were compared to the average growing season chlorophyll *a* levels for scenario 1C. Twenty years of modeling results for all surface grid cells were evaluated. Figure 4-6 displays the results for Lake Burton for years 2001-2020. The solid red lines capture the upper and lower bounds of most data.



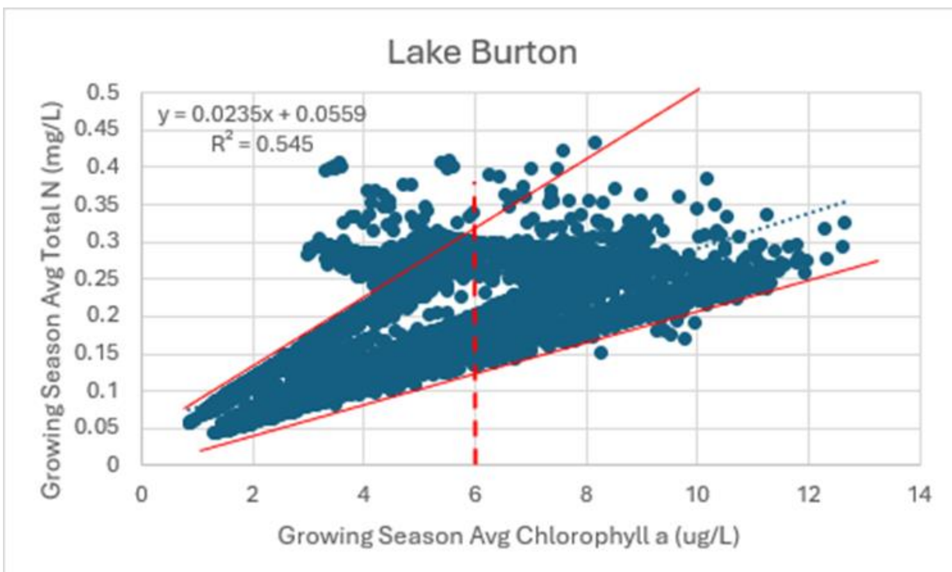
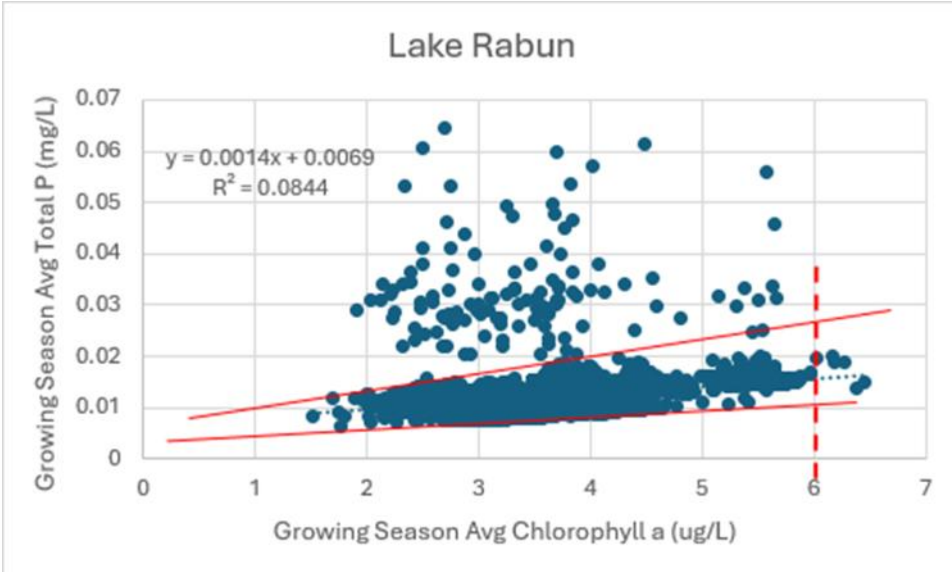


Figure 4-6. Relationship Between Modeled Causal and Response Parameters for Surface Layer of Lake Burton

Figure 4-7 displays the results for Lake Rabun covering years 2001 to 2020.



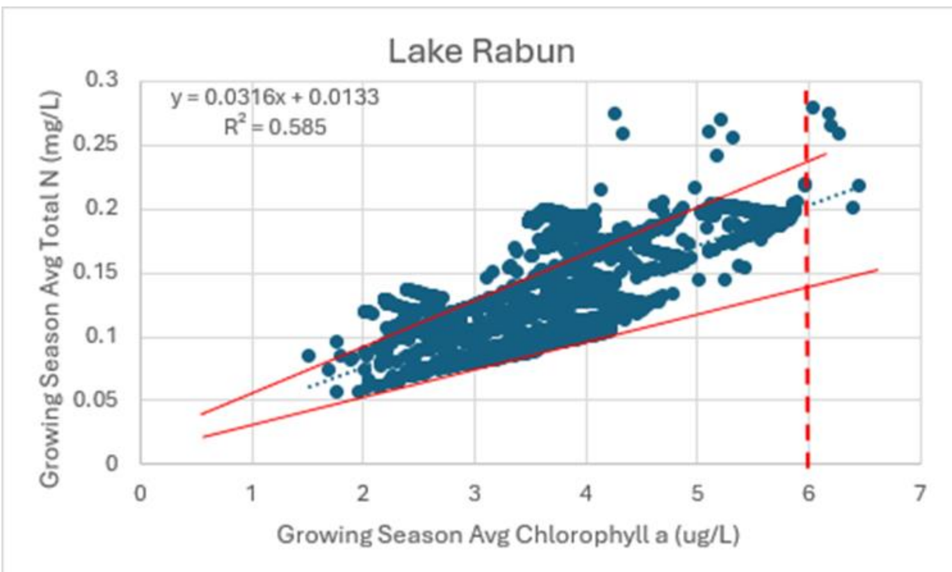


Figure 4-7. Relationship Between Modeled Causal and Response Parameters for Surface Layer of Lake Rabun

4.2 Dissolved Oxygen Results

Modeled results for DO were evaluated for Lakes Burton, Rabun, and Tugalo. In each case, a volume-weighted average for the top two model layers was calculated to represent the DO values of the epilimnion over the 20-year model period. Figures 4-8, 4-9, and 4-10 display the time-series plots of modeled DO in the grid cells that correspond to the Dam Pool and Midlake monitoring locations where EPD has collected data for each lake, respectively.

The Lake Burton results show that the Midlake station stays above the DO minimum of 4 mg/L throughout the model period and the Dam Pool station remains above the DO minimum of 4 mg/L a majority of the modeling period. There are brief excursions below 4 mg/L at the Dam Pool model grid cell during in August and September 2017 (one 6-hour result each month), October 2018 (two 6-hour results in one day), and August and September 2020 (25 6-hour results across 8 days). The Lake Rabun results show that both the Midlake and Dam Pool stations stay above the DO minimum of 4 mg/L throughout the model period. Similarly, the Lake Tugalo results show that both the Mid Lake and Dam Pool stations stay above the DO minimum of 4 mg/L throughout the model period.

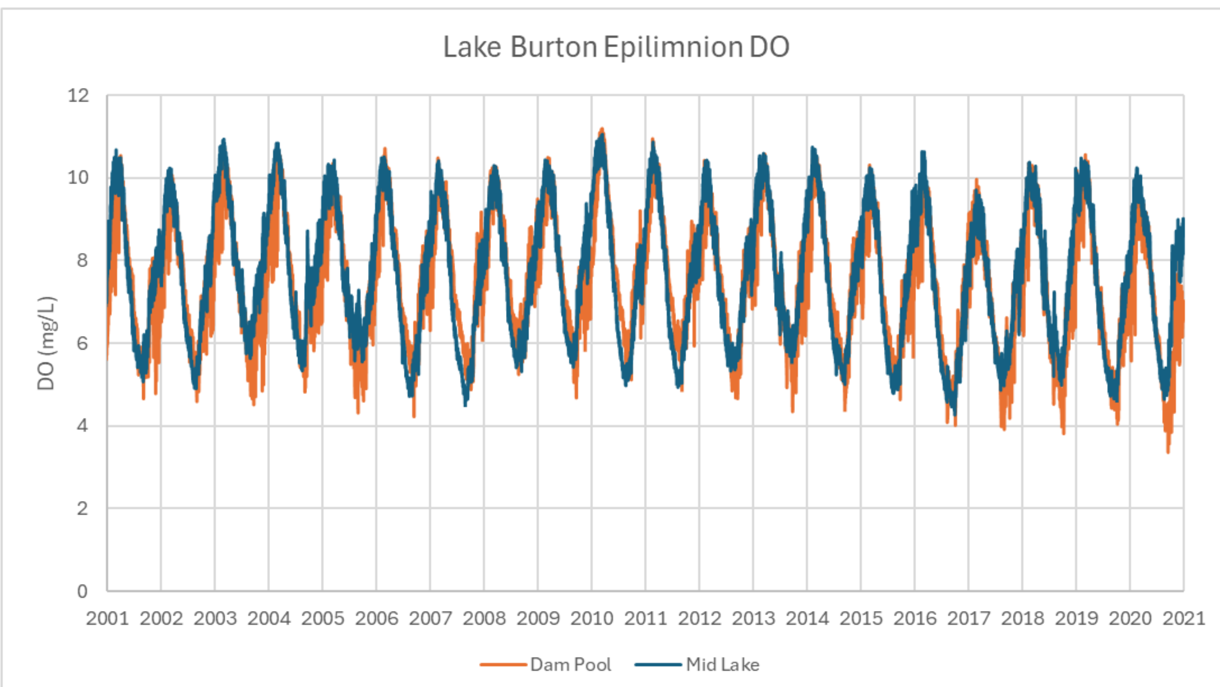


Figure 4-8.Lake Burton Modeled DO in the Epilimnion

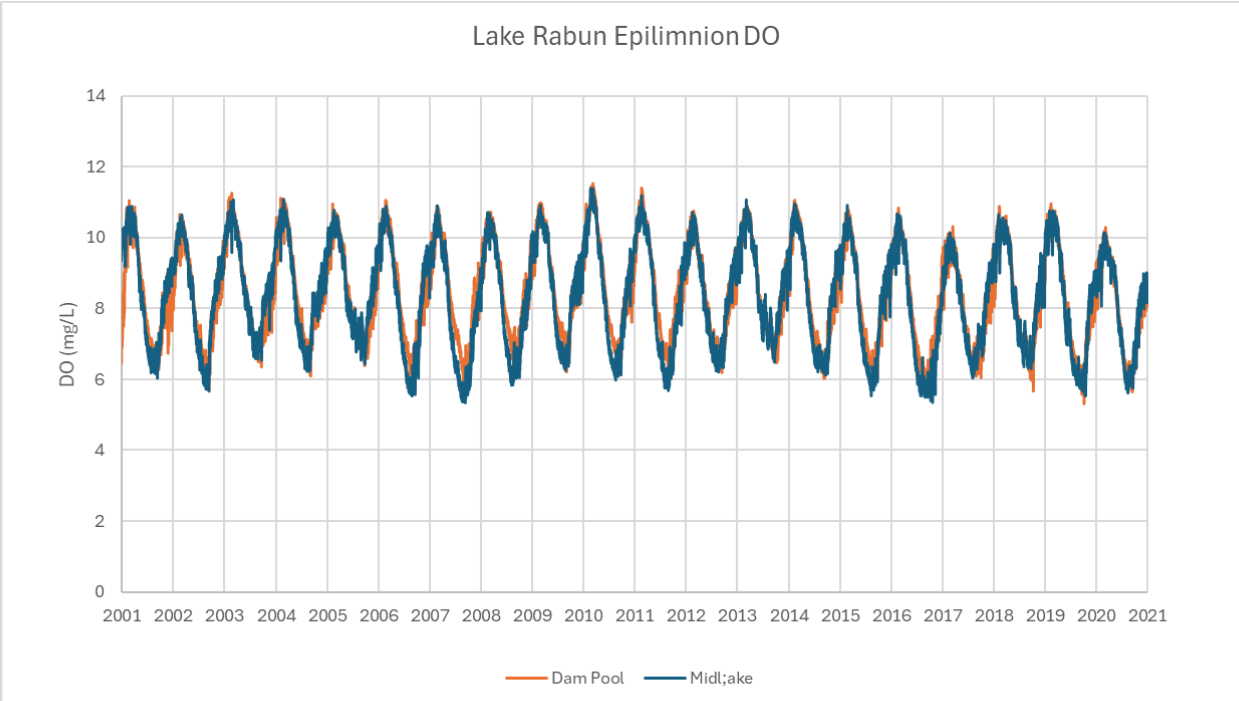


Figure 4-9. Lake Rabun Modeled DO in the Epilimnion

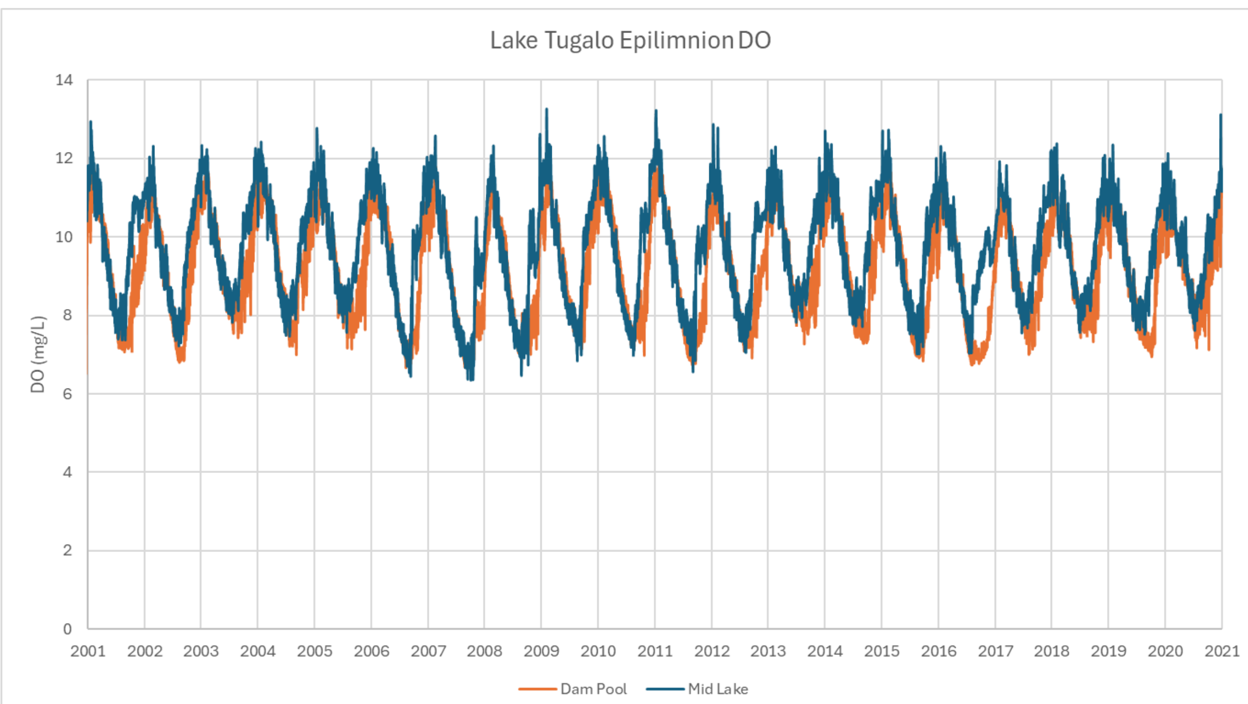


Figure 4-10. Lake Tugalo Modeled DO in the Epilimnion

Figures 4-11, 4-12, and 4-13 present the median modeled DO value over the 20-year model period for each model grid cell in each lake. The graduated color maps display the range of median DOs in each lake. Lake Burton shows the widest variation, with one cell just below 7 mg/L and the remaining cells between 7 and 10 mg/L. Lake Rabun shows the least variation with all grid cells except the headwater cell having a DO between 8 and 9 mg/L. The range of values in Lake Tugalo are similar to those in Lake Burton; however, the influence of the higher DO water from the Chattooga River can be clearly seen. The Tallulah River arms has DO lower by almost 1 mg/L.

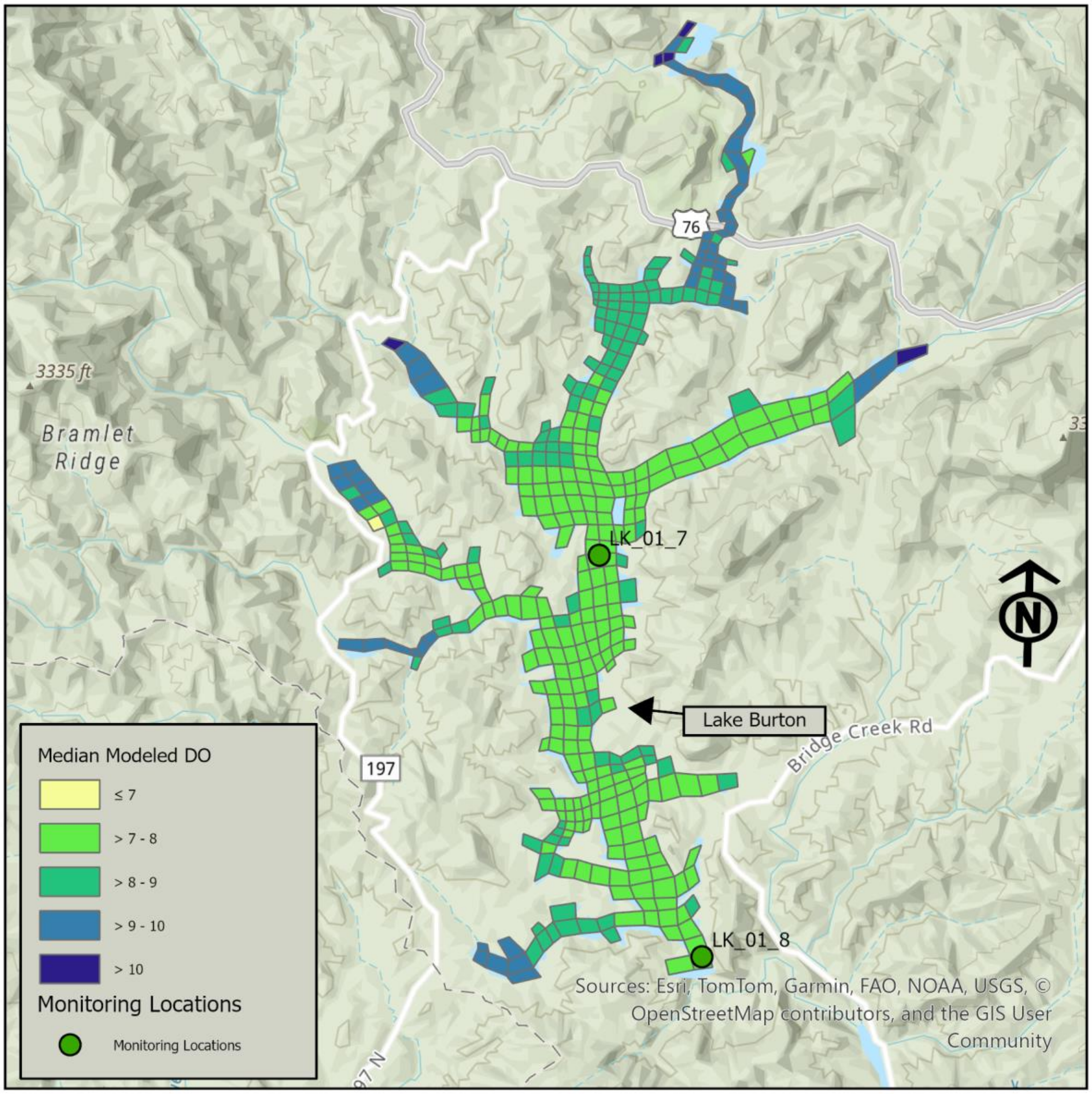


Figure 4-11. Median Modeled DO in the Epilimnion throughout Lake Burton

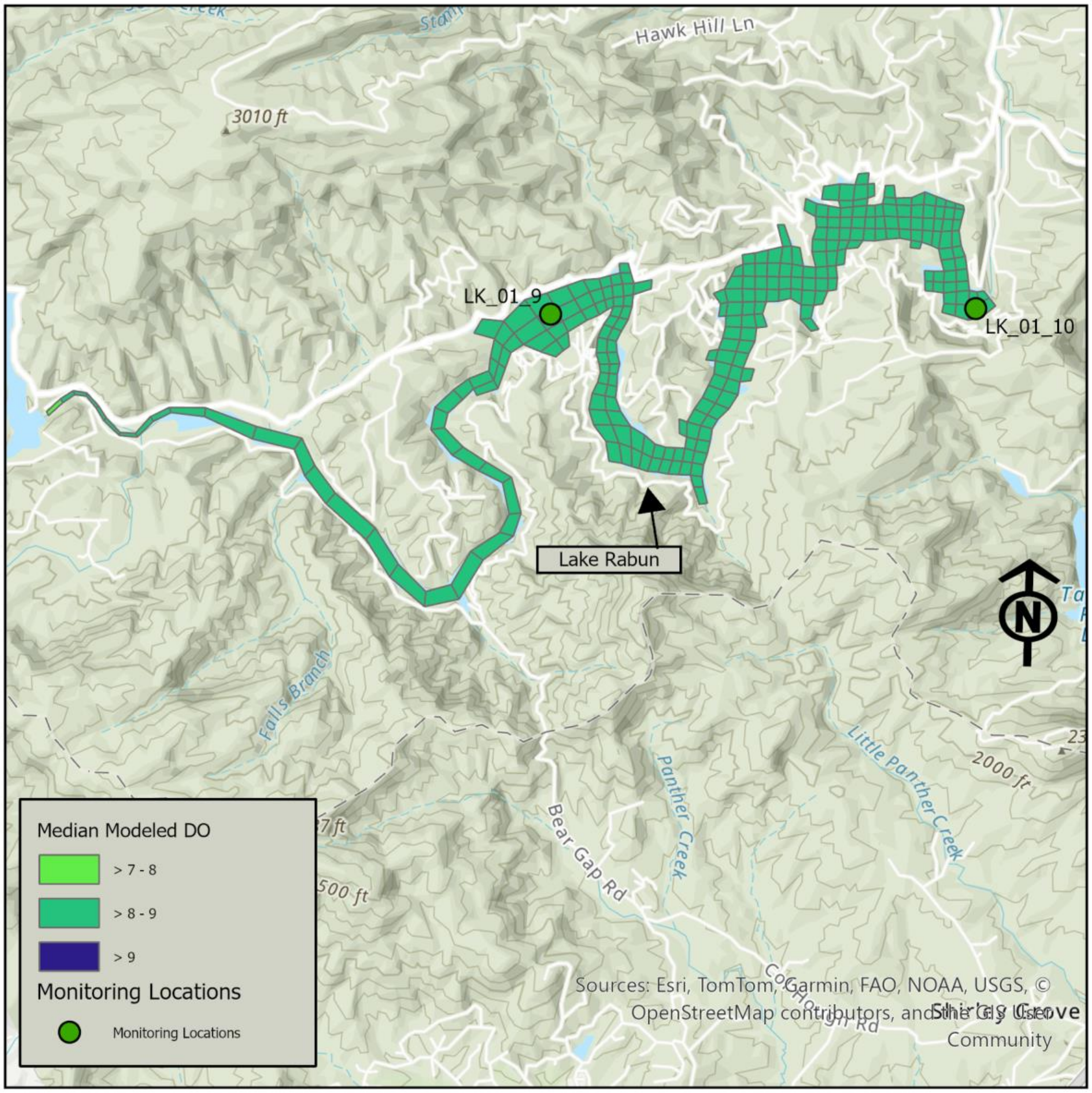


Figure 4-12. Median Modeled DO in the Epilimnion throughout Lake Rabun

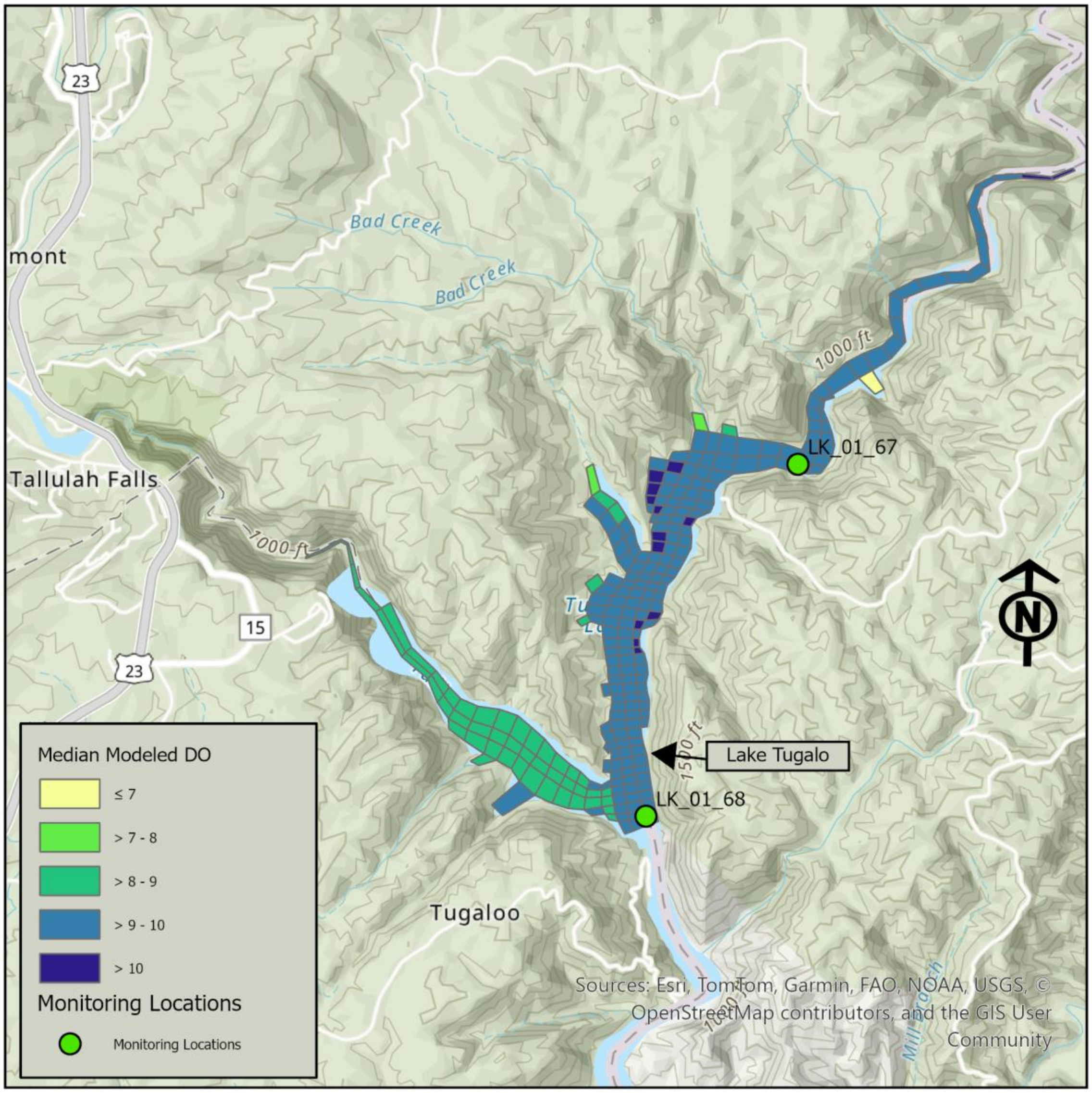


Figure 4-13. Median Modeled DO in the Epilimnion throughout Lake Tugalo

5.0 DESIGNATED USE SUPPORT

Lakes Burton and Tugalo have the designated use of recreation, whereas Lake Rabun has designated uses of recreation and drinking water. Both recreation and drinking water designated uses also support the fishing designated use. The proposed criteria have been selected to protect the established designated uses for all three lakes. Water quality modeling shows that the proposed criteria coupled with the point source nutrient management strategy will protect existing designated uses. GA EPD's point source nutrient management strategy will require nutrient limits for permitted dischargers.

5.1 Recreational Use Support

Lakes Burton, Rabun, and Tugalo are mountain lakes with high water clarity, For data collected from 2014 through 2024, the average Secchi depths for the Dam Pool monitoring locations of Lakes Burton, Rabun, and Tugalo are 3.7, 3.4, and 2.6 meters, respectively, with average photic zones of approximately 9.5, 9.0 and 6 meters, respectively. These lakes are ideal for swimming and recreation in and on the water. Figure 5-1 presents a diagram of the relationship between nutrients and other factors that recreation use.

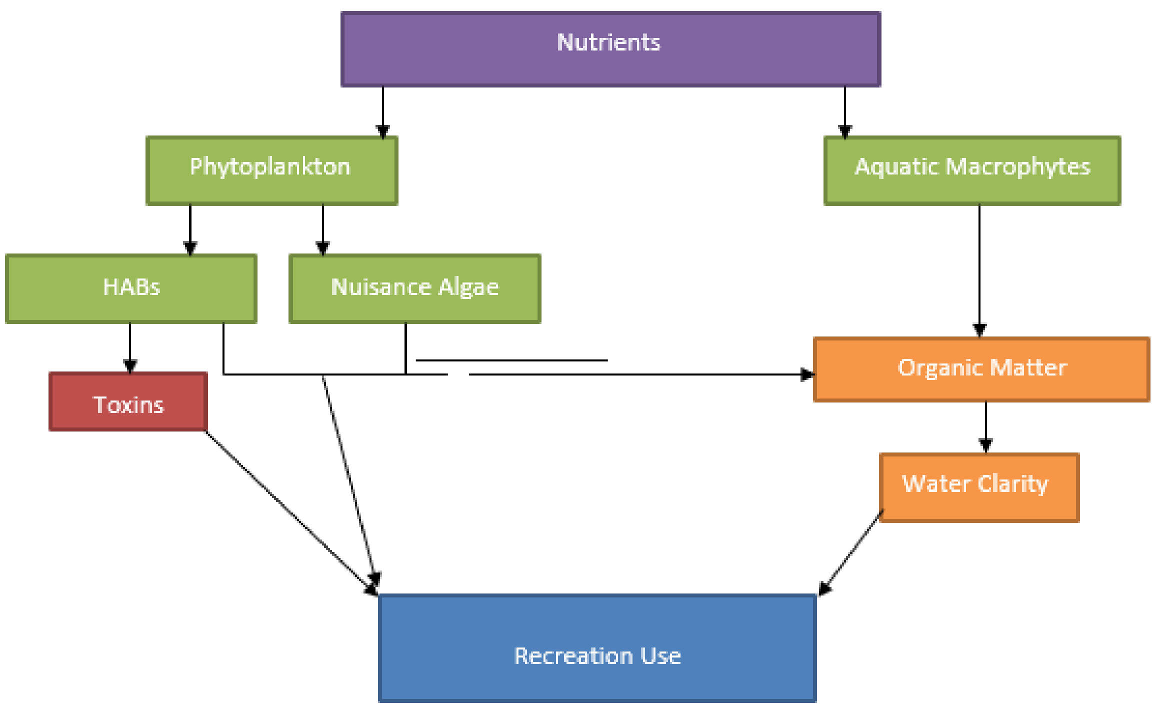


Figure 5-14. Recreation Use Schematic

5.1.1 Cyanobacteria Blooms

Occasionally, naturally occurring populations of algae, including blue-green algae (cyanobacteria), exhibit exponential growth patterns that result in extremely high cell densities referred to as a “bloom.” Cyanobacteria (blue-green algae) are photosynthetic bacteria that share some properties with algae. When conditions are favorable, cyanobacteria can rapidly multiply, resulting in "blooms." Some species of cyanobacteria produce toxins, known as cyanotoxins. These blooms are usually temporary and typically occur during warm weather. From an ecological perspective, visible algae signify alterations in the ecosystem with potential for low dissolved oxygen levels, reduced water clarity, and high bacteria levels.

In 2015, Georgia Power developed an assessment and response protocol for blooms, which uses a visual-based cyanobacteria bloom assessment method patterned after a procedure used by the State of Vermont (Georgia Power, 2014). The method document is entitled, Cyanobacteria Bloom Assessment and Response Guideline for Georgia Power Company Lakes (Rev. January 18, 2024). Georgia Power’s Regional Shoreline Managers and certain Natural Resources personnel are trained to recognize cyanobacteria blooms. They are Georgia Power’s frontline response team for observations of potentially toxic algae blooms. However, initial observations of blooms or suspected blooms often first come from a variety of sources including lake recreationists, shoreline homeowners, anglers, and marina operators. Visual observations are made in the normal course of shoreline managers’ frequent inspections on the lakes. Typically, the potential for algal bloom development begins at the beginning of the summer.

If a bloom condition is detected, Georgia Power personnel would conduct the Visual Bloom Assessment which results in a Condition Category or stage of bloom development based on a standard protocol including water clarity, color, particle density, bloom appearance, and a photo-based visual guide. A Visual Bloom Assessment finding of an advanced bloom (Condition Category 3) can be followed by laboratory-based lake water sample analysis (Sample Assessment), if necessary, The Sample Assessment can inform decision makers with additional ecological and toxicity details of the bloom. If an observed cyanobacteria bloom is shown to have toxic properties, Georgia Power, at a minimum, notifies GA EPD’s Watershed Protection Branch and Georgia Wildlife Resources Division (WRD) as soon as possible and as warranted, a coordinated decision is made regarding beach closures and/or swim advisories. If a beach has a history of algal blooms, frequent monitoring would be warranted.

Lakes Burton, Rabun, and Tugalo have not had any recorded cyanobacteria blooms and there have been no recreational closures at the Georgia Power operated beach on Lake Burton (personal communication, Tony Dodd – Georgia Power) or the United States Forest Service (USFS) operated beach on Lake Rabun (personal communication, Barbara Ramey - USFS) due to harmful algal blooms (HAB) thus they are supportive of the recreational designated use.

5.2 Fishing Use Support

Water quality to support the reproduction, growth, and survival of fish is essential. Pure water will not support fish production. Water must have suitable physical (e.g., temperature), chemical (e.g., pH, minerals, dissolved oxygen, contaminants), and biological (e.g., chlorophyll) characteristics to support a healthy fishery. Water clarity is affected by all these characteristics and, in conjunction with water temperature, dissolved oxygen, and chlorophyll levels, reflects the best fish habitat conditions. Preferences for certain water quality vary among fish species and among life stages for many species. Changes in water quality can affect fish production including egg survival and hatching rates, survival of fish larvae, feeding habits of juvenile and adult fish, and spawning behavior. Water quality can also affect fish community composition and resiliency. Highly productive waters support different fish communities than waters of low productivity. Generally, highly productive waters favor fish communities comprised of bass, catfishes, minnows, gizzard shad, and sunfishes, whereas waters with limited productivity support trout. Moderately productive waters are ideal for walleye and yellow perch communities. Figure 5-2 presents a diagram of the relationship between nutrients and other factors that impact aquatic life use.

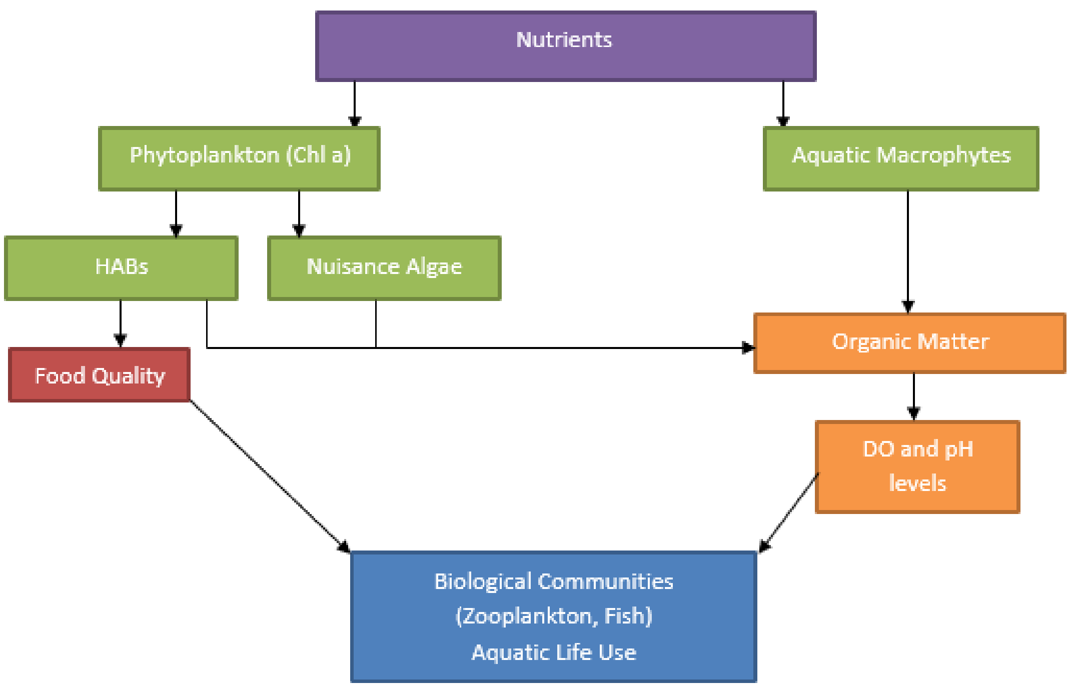


Figure 5-15. Aquatic Life Use Schematic

5.2.1 Lake Burton Fisheries Population

Lake Burton is a 2,775-acre reservoir managed by Georgia Power located near the city of Clayton, Georgia. The Georgia Department of Natural Resources manages the Lake Burton Fish Hatchery and Moccasin Creek State Park located on the lake's west side. The lake is surrounded by a bio-diverse temperate rain forest and this natural environment is a unique resource for both visitors and residents.

The lake supports an excellent bass fishery and is home to the current state record Spotted Bass. The fish was caught in February 2005 and tipped the scales at 8 pounds, 2 ounces. Despite some fluctuations in year-to-year catch rates, the bass population in this reservoir is considered to be in a stable state (see Figure 4-3). The lake is also home to a diverse variety of fish, including White Bass, Black Crappie, Bluegill, Redear Sunfish, White Catfish, Walleye, Brown Trout, Rainbow Trout, and Yellow Perch. Several of its feeder streams are well-known trout streams. No organized fishing tournaments currently occur on Lake Burton, although pop-up weekend events are occasionally seen.

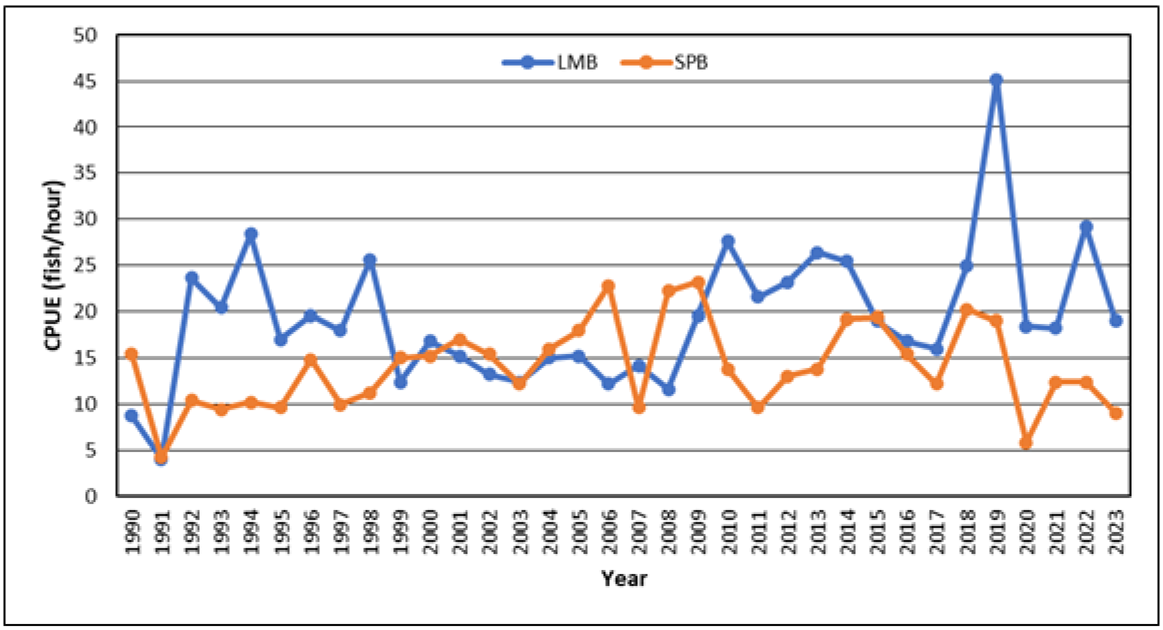


Figure 5-16. Catch-per-unit-effort of Black Bass species (Largemouth Bass and Spotted Bass) sampled from Lake Burton using DC electrofishing from 1990 to 2023

Lake Burton was stocked with Walleye fingerlings in the spring from 1998 to 2007, but they are no longer being stocked. Instead, the lake is now managed with the intent of it being a trophy Brown Trout fishery. Brown Trout stocking rates from 2000 to 2013 ranged from 6,000 to 50,000 fish annually and around 15,000 fish were stocked annually thereafter. Approximately 9,180 catchable-sized Brown Trout were stocked in October of 2023. Brown Trout stocking will continue in the future with a preferred goal of 15,000 fish annually. In addition to stocking Lake Burton, trout are routinely stocked into Moccasin Creek, which feeds directly into Lake Burton. Occasional fish kills occur in early summer and are associated with post-spawn bacterial infections. Winter die-offs of Blueback Herring occur in February when water temperatures drop below 45°F for an extended period of time.

Standardized sampling for this lake includes spring boat electrofishing and fall gill netting surveys that have been taking place since 1987 and 1986, respectively. Electrofishing primarily targets Centrarchidae species while they are in shallow water for spawning, while gill netting is a versatile, passive gear that targets benthic and pelagic species during cooler water temperatures. Additionally, winter dissolved oxygen and water temperature values have been continually monitored from October through May each year since 2005 via a HOBO data logger in the forebay of the dam. This is done to monitor changes in water quality in the instance of a Blueback Herring kill from low water temperatures.

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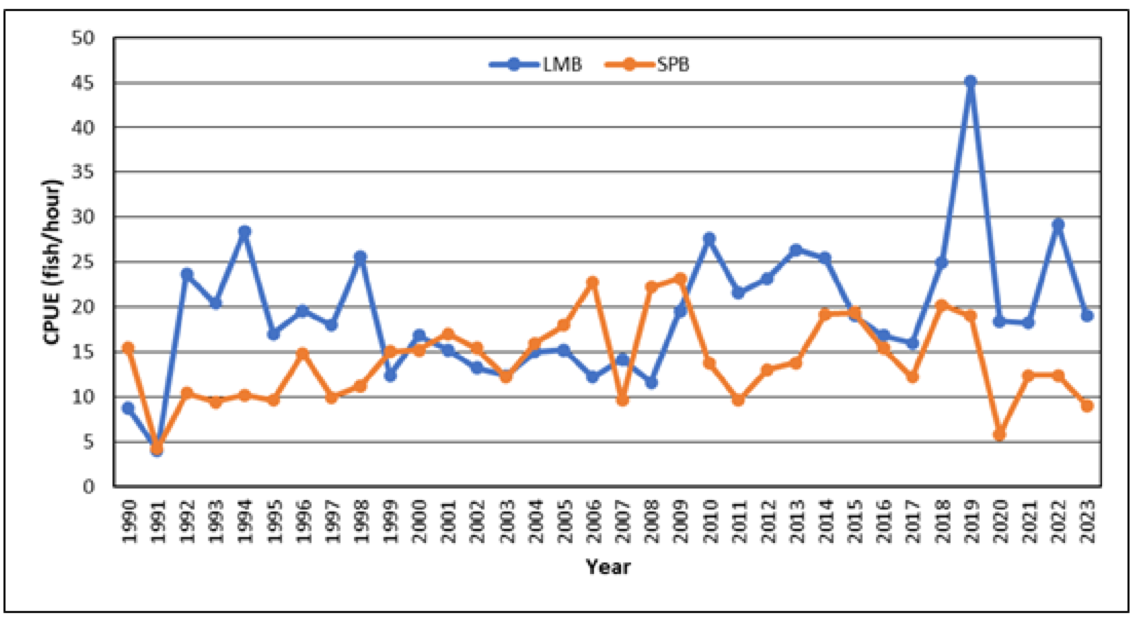

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Standardized sampling for this lake includes spring boat electrofishing and fall gill netting surveys that have been taking place since 1987 and 1986, respectively. Electrofishing primarily targets Centrarchidae (Sunfish) species while they are in shallow water for spawning, while gill netting is a versatile, passive gear that targets benthic and pelagic species during cooler water temperatures. Additionally, winter dissolved oxygen and water temperature values have been continually monitored from October through May each year since 2005 via a HOBO data logger in the forebay of the dam. This is done to monitor changes in water quality in the instance of a Blueback Herring kill from low water temperatures.

The References contain a Fishing Forecast for Lake Burton that outlines the fish species that can be caught in the Lake Burton including the prospect, technique, and target for finding these fish. Measured chlorophyll a data ranges from less than 1 to 6 ug/L, indicating the lake is oligotrophic to mesotrophic. These levels support the Lake Burton black bass populations; although research by Dr. M. J. Maceina et al and Dr. M. S Allen et al of Auburn University, indicate levels of black bass recruitment increase in more productive lakes. Trout are predatory fish and do not rely directly on chlorophyll a levels. However, they need a healthy ecosystem where chlorophyll-producing phytoplankton, the base of the food chain, supports the insects that trout consume. The proposed chlorophyll criteria of 6 ug/L will support the diverse Lake Burton fish populations and should have little to no effect on the DO and pH levels of the lake. Measure DO data in the epilimnion are typically above 7 mg/L. These data are agreement with the volume weighted DO from the top two layers of the Lake Burton model that shows the median DO is typically above 7.2 mg/L. These DO levels are supportive of the Largemouth Bass, Spotted Bass, and Brown Trout fisheries and support the other fish found in the Lake Burton. Lake Burton is a mountain lake with a relatively small drainage area fed by mountain streams whose source waters are springs with low pH, less than 6.0 SU. Measured pH data in the Lake Burton epilimnion are typically between 6 and 7 SU. However, in May and July 2019, the pH dropped to 5.5 at the

Midlake and Dam Pool monitoring stations. These pH levels were temporary and still supported the Lake Burton Fishery.

5.2.2 Lake Rabun Fisheries Population

Lake Rabun is an 835-acre reservoir managed by Georgia Power near the City of Lakemont, Georgia. It is just a few miles downstream of Lake Burton. This lake supports an excellent bass fishery and currently holds the title for having the state record Walleye at 14 pounds, 2 ounces. The upper two miles of the reservoir are more riverine and are shallow and rocky near the headwaters just below Nacoochee Dam. Despite some fluctuations in year-to-year catch rates, the bass population in this reservoir is in a stable state (see Figure 4-4). Black Crappie, Bluegill, Largemouth Bass, Redear Sunfish, Spotted Bass, Walleye, and Yellow Perch are the favorite sport fish species targeted by local anglers. No organized fishing tournaments currently occur on Lake Rabun.

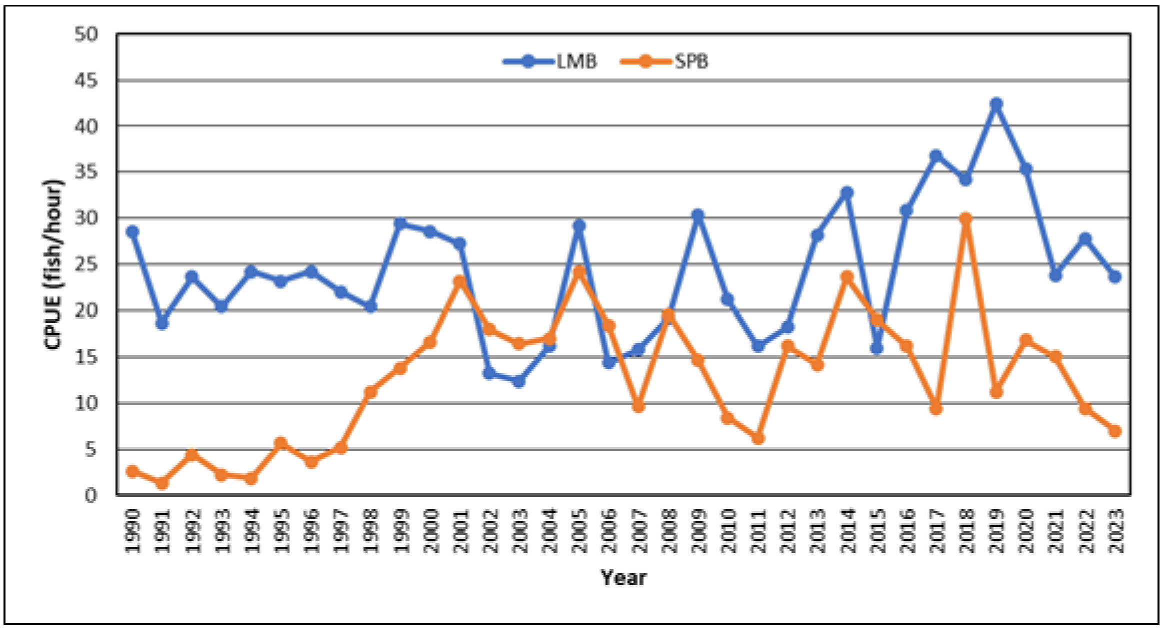

Figure 5-18. Catch-per-unit-effort of Black Bass species (Largemouth Bass and Spotted Bass) sampled from Lake Rabun using DC electrofishing from 1990 to 2023

The lake has been stocked with Walleye fingerlings in the spring since 2005. The preferred stocking rate for the reservoir is 25 fish/acre with a maximum rate of 50 fish/acre. Most years have stocking rates that fall between these two values, although there have been a few exceptions to that rule (see Figure 4-5). Walleyes need low water clarity and DO levels above a daily average of 5.0 mg/L not less than 4.0 mg/L but DO levels above 6.0 mg/L are best for Walleye growth. Walleye prefer waters with pH ranges from 6.0 to 8.0. Below a pH of 6.0, Walleye spawning and recruitment decrease. Lab tests have shown that Walleyes grow fastest at temperatures between 68°F and 75°F, avoiding water over 75°F. Growth of adults apparently stops below 53°F, and temperatures between 84°F and 95°F have proven fatal. Major Walleye spawning areas are in the headwaters in very shallow water with rocky bottoms, like the headwaters of Lake Rabun. In the late spring and summer after spawning season, Walleye return to the main lake to resume their daily ritual of finding food and searching for sheltered resting areas. Because walleye prefer cool water temperatures (65 to 72ºF), during the summer months small schools of walleye will congregate together in deeper water where temperatures are more suitable. Winter die-offs of Blueback Herring can occur in February when water temperatures drop below 45°F for an extended period of time.

Standardized sampling for this lake includes spring boat electrofishing and fall gill netting surveys which have been taking place since 1987 and 1986 respectively. Electrofishing primarily targets Centrarchidae species while they are in shallow water for spawning, while gill netting is a versatile, passive gear that targets benthic and pelagic species during cooler water temperatures to help reduce mortality. Additionally, winter dissolved oxygen and water temperature values have been continually monitored from October – May each year since 2006 via a HOBO data logger in the forebay of the dam. This is done to monitor changes in water quality.

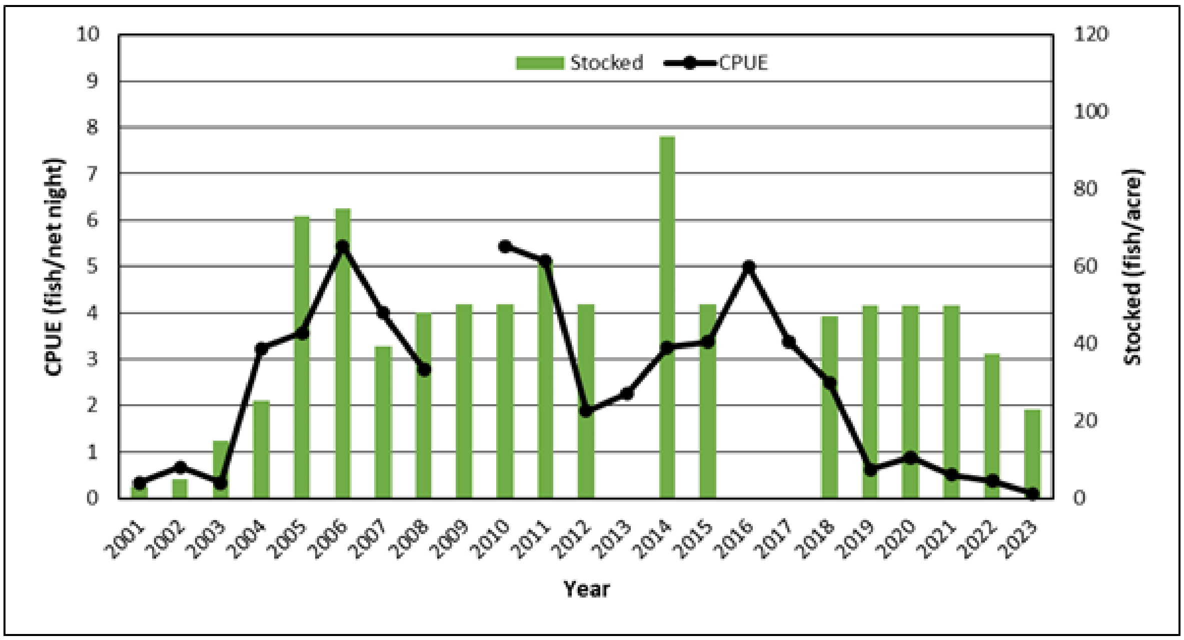

Figure 5-19. Catch-per-unit-effort of Walleye sampled from Lake Rabun using gill netting alongside spring stocking numbers of fingerlings from 2001 to 2023

The References contain a Fishing Forecast for Lake Rabun that outlines the fish species that can be caught in the Lake Rabun including the prospect, technique, and target for finding these find. Measured chlorophyll a data in Lake Rabun ranges from less than 1 to 7 ug/L, indicating the lake is oligotrophic to mesotrophic. These levels support of both walleye and black bass populations in the lake, Walleye recruitment like black bass recruitment increases in more productive lakes and the proposed chlorophyll *a* criteria of 6 ug/L will support the fishing designated use. However, Walleye do moderately productive mesotrophic lakes. Measured DO data in the epilimnion are greater than 7 mg/L at Midlake and between 6 and 7 mg/L at the Dam Pool. These data are agreement with the the volume weighted DO from the top two layers of the Lake Rabun model that shows the median DO above 8.0 mg/L and the minimum DO above 5.0 mg/L. These DO levels are supportive of the Largemouth Bass, Spotted Bass and Walleye fisheries and support the other fish found in the Lake Rabun. Lake Rabun is a mountain lake with a relatively small drainage areas fed by Lake Burton and mountain streams whose source waters are springs with low pH <6.0 SU. Measured pH data in the Lake Rabun epilimnion are typically between 6 and 7 SU. However, in July 2019, the pH dropped to 5.5 at the Midlake monitoring station. These pH levels were temporary and still supported the Lake Rabun fishery.

5.2.3 Lake Tugalo Fisheries Population

Lake Tugalo is a 597-acre lake formed by the confluence of the Chattooga and Tallulah Rivers. Owned and operated by Georgia Power, Lake Tugalo lies on the Georgia-South Carolina border near the City of Clayton and just a few miles downstream of Tallulah Falls Lake. To maintain the pristine aspects of this small reservoir, outboard motors are restricted to 25 horsepower. Both Largemouth and Spotted Bass occur in good numbers in Lake Tugalo and are in a stable state despite some fluctuations in year-to-year catch rates. Lake Tugalo has displayed more resistance to the spread of Spotted Bass compared to other nearby mountain lakes, with Spotted Bass numbers staying relatively low in relative abundance (see Figure 4-6). This unique reservoir also offers good fishing for Channel Catfish and Walleye, boasting the best catch rates for Walleye compared to surrounding stocked lakes. In addition to a quality sunfish fishery consisting of large Bluegill, Redbreast Sunfish, and Redear Sunfish, Tugalo also provides seasonal opportunities to catch White Bass. No organized fishing tournaments currently occur on Lake Tugalo.

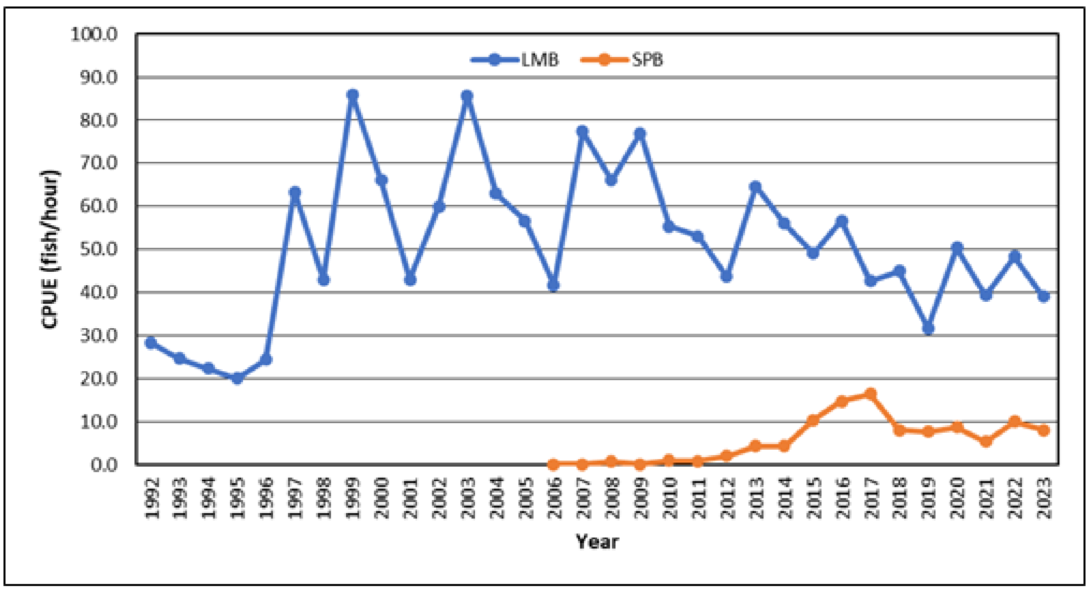

Figure 5-20. Catch-per-unit-effort of Black Bass species (Largemouth Bass and Spotted Bass) sampled from Lake Tugalo using DC electrofishing from 1992 to 2023

Lake Tugalo has been stocked with Walleye fingerlings in the spring since 2005 (see Figure 4-7). The preferred stocking rate for the reservoir is 50 fish/acre with a maximum rate of 75 fish/acre. Most years have rates that fall between these two values, although there have been a few exceptions to that rule. Again, Walleye need low water clarity, DO levels above a daily average of 5.0 mg/L not less than 4.0 mg/L, pH ranges from 6.0 to 8.0, and cool water temperatures (65 to 72ºF), which can be found in Lake Tugalo, making it one of the best Walleye lakes in Georgia. Winter die-offs of Blueback Herring can occur in February when water temperatures drop below 45°F for an extended period of time.

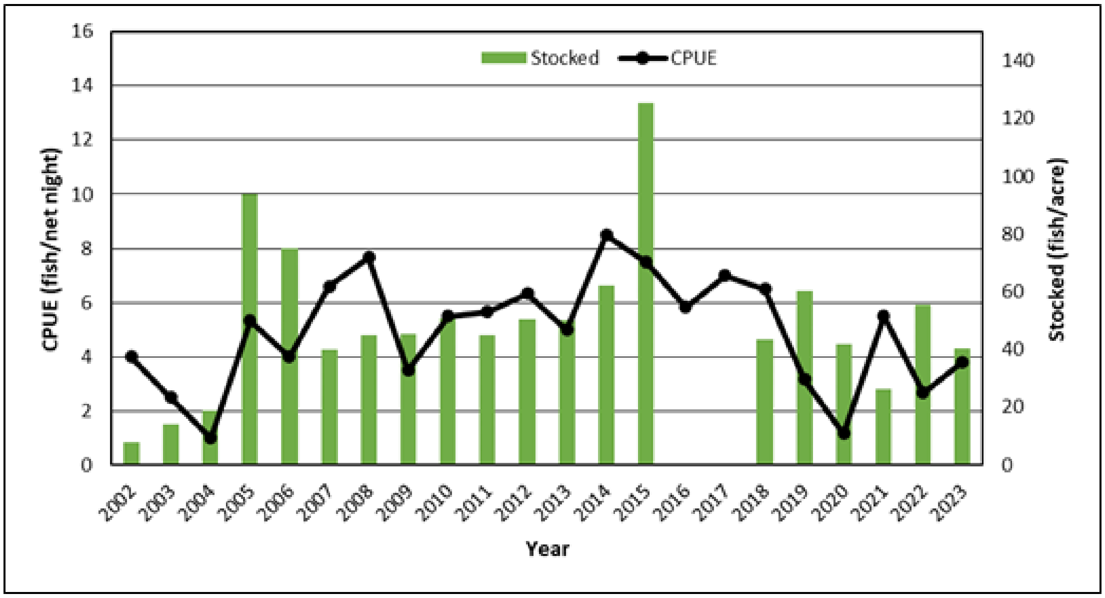

Figure 5-21. Catch-per-unit-effort of Walleye sampled from Lake Tugalo using gill netting alongside spring stocking numbers of fingerlings from 2002 to 2023

Standardized sampling for this lake includes spring boat electrofishing and fall gall netting surveys which have been taking place since 1987 and 1986 respectively. Electrofishing primarily targets Centrarchidae species while they are in shallow water for spawning, while gill netting is a versatile, passive gear that targets benthic and pelagic species during cooler water temperatures to help reduce mortality. Additionally, winter dissolved oxygen and water temperature values have been continually monitored from October through May each year since 2006 via a HOBO data logger in the forebay of the dam. This is done to monitor changes in water quality in the instance of a Blueback Herring kill from low water temperatures.

The References contain a Fishing Forecast for Lake Tugalo that outlines the fish species that can be caught in the Lake Tugalo including the prospect, technique, and target for finding the find. The reduced clarity and slightly higher proposed chlorophyll a level of 7 ug/L support the higher diversity of fish found in Lake Tugalo. Measured chlorophyll a data in Lake Tugalo ranges from less than 1 to 9 ug/L, indicating the lake is oligotrophic to mesotrophic. These levels support of walleye, yellow perch, largemouth bass, spotted bass, white bass, bream, and catfish populations in the lake and the proposed chlorophyll *a* criteria of 7 ug/L will support the fishing designated use. Walleye recruitment like black bass recruitment increases in more productive lakes. However, Walleye do best in moderately productive mesotrophic lakes. Measured DO data in the epilimnion are typically greater than 7 mg/L at Midlake Dam Pool. These data are agreement with the the volume weighted DO from the top two layers of the Lake Tugalo model that shows the median DO is typically above 7.7 mg/L with a minimum around 5.5 mg/L. These DO levels are supportive of the Lake Tugalo fishery. Lake Tugalo is a mountain lake with a relatively small drainage areas fed by Lake Rabun, Stekoa Creek, Chattooga River and mountain streams whose source waters are springs with low pH <6.0 SU. But can drop as low as 5.5. These pH levels appear to be temporary and their spatial and temporal extent will need to be further investigated. However, the fish species that inhabitant Lake Tugalo seem to tolerant lower pH levels.

5.3 Drinking Water Source Use Support

Water quality is also important for waters used as drinking water sources. The protection of public drinking water systems falls under the Safe Drinking Water Act and EPA has set standards for finished drinking water that fall into two categories: Primary Standards and Secondary Standards. Primary Standards protect human health considerations from three classes of pollutants: microbial pathogens, radioactive elements, and organic/inorganic chemicals. Many of these contaminants occur naturally in trace amounts in surface water. Limits called Maximum Contaminant Level (MCL) have been set for these Primary Standards, and these are the highest allowable concentration of a pollutant in drinking water supplied by public water systems. Secondary Standards regulate parameters that cause offensive taste, odor, color, corrosivity, foaming and staining. Public water systems are not required to test for or remove secondary contaminants. Secondary Standards are guidelines for water treatment plant operators and state governments attempting to provide communities with the best quality water possible. Ideal source water for drinking water plants will have no contaminants, low total organic carbon (TOC), low turbidity, and low total dissolved solids (TDS) thus reducing the treatment costs and avoiding the need for complex treatment. Figure 5-8 presents a diagram of the relationship between nutrients and other factors that impact drinking water use.

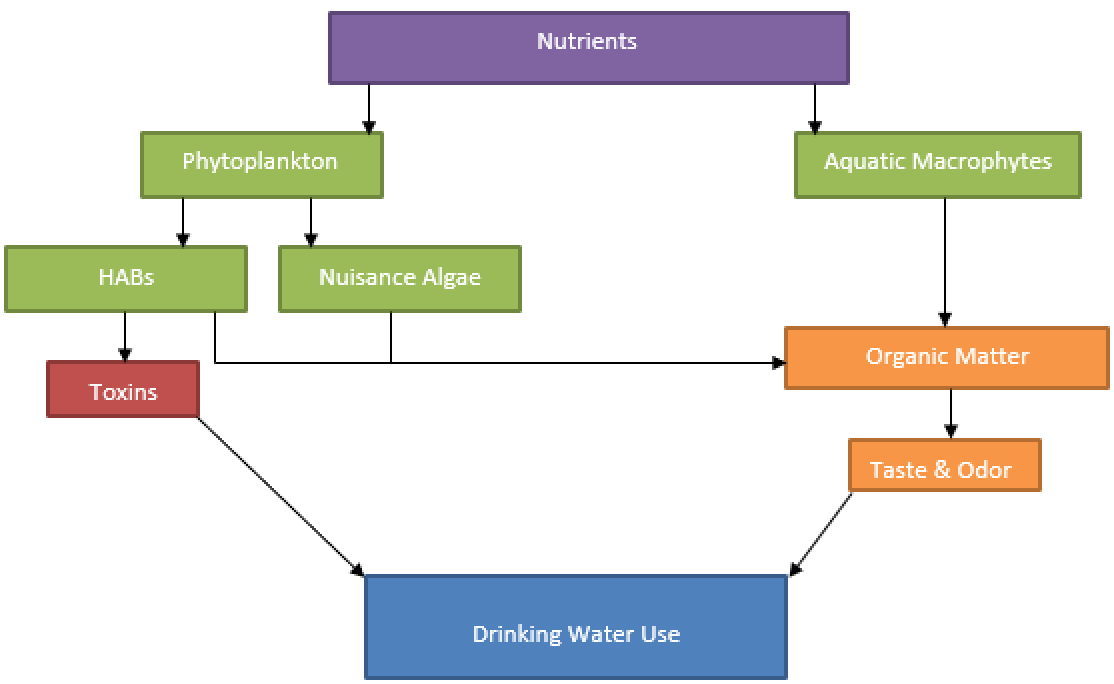

Figure 5-22. Drinking Water Use Schematic

No permitted drinking water intakes exist on either Lake Burton or Lake Tugalo.

5.3.1 Lake Rabun Intake

Lake Rabun has one drinking water intake, the Lake Rabun Water Treatment Plant, owned and operated by Rabun County Water and Sewer Authority. The Rabun County Water and Sewer Authority reports no taste and odor problems in the plant due to algae in the lake. There has been a slight smell during the rinsing of the clarifiers, but there are no taste or odor problems in the finished tap water. Bleach takes care of the odor in the clarifiers. During the fall there are higher manganese levels, but nothing close to the secondary maximum contaminant level SMCL (personal communication, Tracia Taylor, RCWSA). GA EPD has received no complaints filed in our complaint tracking system within the last five years. Lake Rabun's high clarity, low turbidity, low TOC, and low TDS levels, along with the proposed chlorophyll a criteria of 6 ug/L are protective of the Drinking Water Supply designated use.

5.4 Downstream Uses

Downstream of Lakes Burton, Rabun, and Tugalo, is Lake Yonah, which continues to flow into Lake Hartwell and joins the Savannah River, which then flows into Lakes Russell and Clark's Hill and eventually empties into the Savannah Harbor. The designated uses of Lake Yonah are drinking water, recreation, and fishing. Currently, the downstream lakes do not have numeric nutrient or chlorophyll criteria. However, the water quality criteria for these waters will be protected. GA EPD is currently working to develop a watershed and hydrodynamic water quality models that will be used to develop numeric nutrient criteria for these lakes, as well as the Savannah Harbor estuary, which is the terminus water downstream from Lakes Burton, Rabun, and Tugalo.

Table 5-1 shows all the segments downstream of Lake Tugalo and their assessment status. The majority of impairments are for PCBs and Thallium in fish tissue. The proposed chlorophyll *a* and nutrient criteria for Lakes Burton, Rabun, and Tugalo are not expected to impact downstream uses. Since the proposed lake criteria were derived based partially on historical data, and because all the lakes and the waterbodies downstream have historically met their designated uses, the proposed criteria are not expected to impact downstream uses.

Currently, there are no numeric nutrient criteria for rivers, streams, or estuaries. Due to the harbor traffic, the Savannah Harbor is not routinely monitored for nutrient and chlorophyll. However, there are several continuous water quality monitors located throughout the harbor that monitor the dissolved oxygen, temperature, pH, and salinity levels.

Table 5-2. Assessment Status of Lake and Stream Segments Downstream of Lake Tugalo

2024 Integrated 305(b)/303(d) List

Reach Name/ID	Reach Location/County	River Basin/ Use	Assessment/ Data Provider	Cause/ Source	Size/Unit	Category/ Priority	Notes
Yonah Lake	Near Tallulah Falls, Georgia	Savannah	Assessment Pending		146.5	2	TMDL completed Fish Tissue (Hg) 2005. The water is supporting its Fishing use. There is not data available to assess the Recreation and Drinking Water uses.
GAR030601020407	Habersham, Stephens	Drinking Water, Recreation, Fishing	1		Acres		
Hartwell Lake	Tugaloo Arm/ Main Body	Savannah	Not Supporting	Fish Tissue (PCBs)	55950	4a	TMDLs completed Fish Tissue (PCBs) (1998) & Cu (2000). The water is meeting its Drinking Water and Recreation Uses, but is impaired for the Fishing Use. Fish Tissue (Mercury) is in Category 3 because at one site the Trophic Weighted Residue was between 0.25 mg/kg and 0.30 mg/kg.
GAR030601030201	Hart, Franklin	Drinking Water, Recreation, Fishing	1,58	I2	Acres		
Savannah River	Lake Hartwell to Cedar Creek	Savannah	Supporting		5	1	TMDL completed DO 2000.
GAR030601030409	Hart	Fishing	1		Miles		
Savannah River	Clarks Hill Lake Dam to Stevens Creek Dam	Savannah	Supporting		12.9	1	TMDL completed DO 2000.
GAR030601060104	Columbia	Drinking Water, Fishing	10		Miles		
Savannah River	Stevens Creek Dam to Horse Creek (formerly Stevens Creek Dam to US 78/278)	Savannah	Supporting		12.2	1	TMDL completed DO 2000.
GAR030601060616	Columbia, Richmond	Drinking Water, Fishing	1		Miles		
Savannah River	Horse Creek to Butler Creek	Savannah	Supporting		10.2	1	
GAR030601060614	Richmond	Fishing	1,10		Miles		
Savannah River	Butler Creek to McBean Creek	Savannah	Not Supporting	Fish Tissue (PCBs), Fish Tissue (Thallium)	21	5	TMDLs completed Pb (2000) and Bacteria (2000)(Revised 2023).
GAR030601060615	Richmond	Fishing	1,10	NP	Miles	2034	
Savannah River	McBean Creek to Johnsons Landing	Savannah	Not Supporting	Fish Tissue (PCBs), Fish Tissue (Thallium)	40	5	
GAR030601060903	Burke, Screven	Fishing	1,10	NP	Miles	2034	

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2024 Integrated 305(b)/303(d) List

Reach Name/ID	Reach Location/County	River Basin/ Use	Assessment/ Data Provider	Cause/ Source	Size/Unit	Category/ Priority	Notes
Savannah River	Johnsons Landing to Brier Creek	Savannah	Not Supporting	Fish Tissue (PCBs), Fish Tissue (Thallium)	24.1	5	The water is supporting its Drinking Water use, but not its Fishing use.
GAR030601060901	Screven	Fishing, Drinking Water	1,9,10	NP	Miles	2034	
Savannah River	Brier Creek to Screven/Effingham County Line	Savannah	Not Supporting	Fish Tissue (PCBs), Fish Tissue (Thallium)	23.4	5	TMDLs completed Pb (1999), Zn (1999). The water is supporting its Drinking Water Use, but is impaired for its Fishing Use.
GAR030601090105	Screven	Fishing, Drinking Water	1,9,10	NP	Miles	2034	
Savannah River	Screnven/Effingham County Line to Ebenezer Creek	Savannah	Not Supporting	Fish Tissue (PCBs), Fish Tissue (Thallium)	29	5	TMDLs completed Pb (1999), Zn (1999). The water is meeting its Drinking Water Use, but not the Fishing Use.
GAR030601090106	Effingham	Fishing, Drinking Water	1,9,10	NP	Miles	2034	
Savannah River	Ebenezer Creek to Seaboard Coastline RR Bridge (upstream Chatham County line)	Savannah	Not Supporting	Fish Tissue (Mercury), Fish Tissue (PCBs), Fish Tissue (Thallium)	20	5	TMDL completed Bacteria 2020. The water is supporting its Drinking Water Use.
GAR030601090322	Effingham	Fishing, Drinking Water	1,10	NP	Miles	2034	
Savannah Harbor	SR 25 (old US Hwy 17) to Elba Island Cut	Savannah	Not Supporting	DO, Fish Tissue (PCBs), Fish Tissue (Thallium)	5	5, 5R	TMDLs completed Bacteria (2000)(Revised 2023), DO (2006) - removed. 5R plan in place to restore water for DO. The source of impairment for DO is UR, M, I1 and the source for the fish tissue impairments is NP.
GAR030601090318	Chatham	Coastal Fishing	1,10,45	UR, M, I1, NP	Square Miles	2034	

5.5 Nutrient NPDES Permitting Strategy

Once EPA approves the proposed Lakes Burton, Rabun, and Tugalo criteria, GA EPD plans to implement a nutrient NPDES permitting strategy. Assuming all facilities in the Burton, Rabun, and Tugalo watersheds were to discharge at the GA EPD nutrient strategy total phosphorus levels, the daily load would be 43.5 lbs/day. GA EPD plans to implement total phosphorus limits according to the Total Phosphorus NPDES Permit Strategy. Without having permit limits in place, it is possible that total phosphorus levels may exceed any proposed total phosphorus criteria.

GA EPD is proposing to adopt chlorophyll *a* criteria for Lake Burton, Rabun, and Tugalo. GA EPD plans to implement appropriate phosphorus and ammonia limits in permits and GA EPD will not be adopting total phosphorus and nitrogen criteria for these lakes at this time. Once the permitted strategy has been implemented, phosphorus and nitrogen criteria for these lakes can be adopted in the future.

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Several agencies provided information for this document and are acknowledged below.

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Fishing Use Support

Fisheries status on Lakes Burton, Rabun, and Tugalo

GADNR WRD Fisheries Biologists (Kyle Rempe)

Drinking Water Source Use Support

GA EPD Watershed Protection Branch, Drinking Water Compliance and Permitting (Matthew Dodd).

Lake Standards Designated Use Review and Assessment

This review was prepared by the DNR EPD Watershed Protection Branch, Watershed Planning & Monitoring Program. Contributors included Elizabeth Booth, Ph.D., Gillian Batson, Tyler Parsons, and Anna Truszczynski.

References

Influence of Trophic State on Spotted Bass and Largemouth Bass Spawning Time and Age-0 Population Characteristics in Alabama Reservoirs

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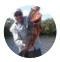

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Influence of Trophic State on Spotted Bass and Largemouth Bass Spawning Time and Age-0 Population Characteristics in Alabama Reservoirs

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Abstract.—We described and compared spawning periodicity, abundance, and growth of age-0 largemouth bass *Micropterus salmoides* and spotted bass *M. punctulatus* from six Alabama reservoirs in 1993 and 1994 that displayed a wide range of limnological and morphological characteristics. One reservoir was divided into three distinct areas based on limnological conditions and thus, eight reservoir study areas were examined. Reservoirs fell along a continuum from deep, long-retention reservoirs with fluctuating water levels and low phytoplankton biomass to shallower, short-retention reservoirs with minimum water level fluctuations and generally high phytoplankton biomass. Fish were collected with rotenone in 0.02-ha enclosed shoreline areas. Daily rings on sagittal otoliths were counted to determine growth rates and to back-calculate spawning times. Trophic states included oligotrophic (chlorophyll *a,* <3 mg/m^3; $N = 1$), mesotrophic (chlorophyll *a,* 3–7 mg/m^3; $N = 4$), and eutrophic (chlorophyll *a,* >8 mg/m^3; $N = 3$) systems. Spotted bass swim-up was slightly earlier than largemouth bass in the two least productive reservoirs in 1993 and 1994. In all other comparisons, spotted bass and largemouth bass spawned at similar times, except in one mesotrophic reservoir where largemouth bass spawned earlier than spotted bass. Spawning duration was slightly longer for largemouth bass. Density and biomass of age-0 largemouth bass varied by an order of magnitude and were higher in the most productive reservoirs. However, age-0 spotted bass biomass was only about twice as great in eutrophic reservoirs compared with the lowest productivity system. Age-0 largemouth bass density exceeded spotted bass density in eutrophic reservoirs, but largemouth bass density and biomass were lower than spotted bass in mesotrophic and oligotrophic reservoirs. Both species grew faster in eutrophic reservoirs, but spotted bass grew faster than largemouth bass in the oligotrophic water body. Although chlorophyll *a* was correlated to other reservoir features, oligotrophication could favor young spotted bass while eutrophication of low-productivity water bodies may select for largemouth bass.

Sympatric populations of largemouth bass *Micropterus salmoides* and spotted bass *M. punctulatus* occur from the Appalachian Divide west to the Great Plains and from the Gulf of Mexico north to the Ohio and Wabash river drainages (MacCrimmon and Robbins 1975). In reservoirs in the southeastern and midwestern United States, spotted bass appear to prefer deep, clear reservoirs with rocky substrate (Vogele 1975). In Cave Run Reservoir, Kentucky, spotted bass and smallmouth bass *M. dolomieu* were more abundant in less productive downstream areas, whereas largemouth bass were abundant in the productive upstream areas (Buynak et al. 1989).

Oligotrophication or eutrophication can alter warmwater sport fisheries and fish community structure (Axler et al. 1988; Yurk and Ney 1989; Ney 1996). For example, oligotrophication could result in a shift in black bass composition from largemouth bass to spotted bass or smallmouth bass (Buynak et al. 1989). Conversely, eutrophication could favor predominance of largemouth bass (Buynak et al. 1989). Angler catch rates of black bass did not differ among Alabama reservoirs that varied in trophic state; however largemouth bass and spotted bass growth, body condition, and size of fish caught by anglers were higher in eutrophic (chlorophyll $a > 8$ mg/m^3) reservoirs than in oligo-mesotrophic (chlorophyll $a < 8$ mg/m^3) water bodies (Maceina et al. 1996).

Undoubtedly, early life processes drive black bass recruitment, probably influencing dominance or codominance of these species. In most instances, year-class strength is determined before the end of the first year (Kramer and Smith 1962; Ludsin and DeVries 1997). Typically, earlier-hatched largemouth bass grow faster and attain greater size than those hatched later, thereby increasing their survival (Miller and Storck 1984; Maceina et al. 1988; Miranda and Hubbard 1994a;

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Ludsin and DeVries 1997). In Lake Normandy, a eutrophic reservoir in Tennessee, largemouth bass initiated spawning before spotted bass during 4 of 5 years, which should favor largemouth bass survival over spotted bass survival (Sammons et al. 1999).

In the six Alabama reservoirs that we examined in this study that contained sympatric populations of largemouth bass and spotted bass, the percentage of age-2 and older spotted bass to all age-2 and older black bass ranged from 4% to 73% (database used in DiCenzo et al. 1995; Maceina et al. 1996) and varied inversely with chlorophyll *a* ($r = -0.92$, $N = 6$, $P < 0.01$). This was consonant with the observations of Buynak et al. (1989) that spotted bass were more common in lower productivity systems.

We sought to quantify time of spawning of spotted bass and largemouth bass in Alabama reservoirs that varied in trophic state. We related growth and abundance of age-0 fish to productivity and other reservoir characteristics to determine if any of these factors were related to dominance by one species early in life. We assumed that the species that spawned earlier would grow faster, be more abundant at young ages, and be more likely to survive to age 1.

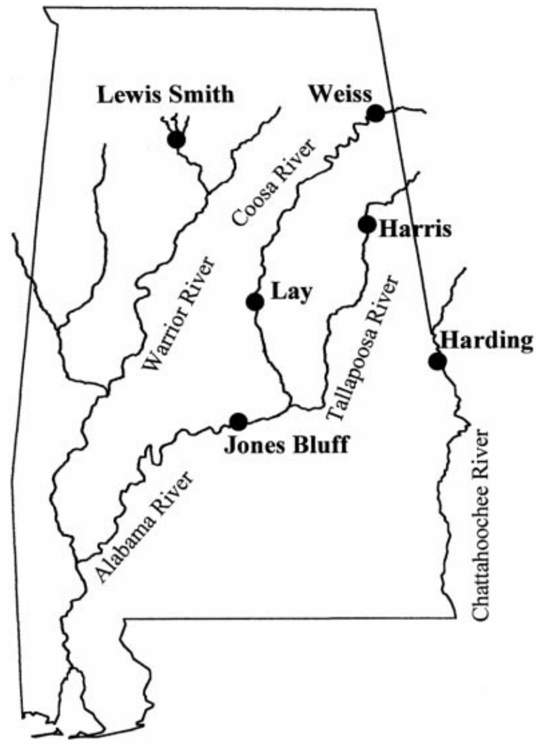

FIGURE 1.—Location of the six study reservoirs in Alabama.

Study Areas

We sampled six reservoirs that contained sympatric populations of spotted bass and largemouth bass (Figure 1). Smith Reservoir was further divided into three areas and included two relatively more productive upstream embayments (Ryan's Creek and Sispey River) and the low-productivity dam forebay (Table 1), which was consistent with the spatial continuum of algal biomass typically found in reservoirs (Wetzel 1990). Distances between sampling areas were greater than 25 km in Smith Reservoir; thus movement of young fish among areas was presumably nil (Copeland and Noble 1994). Trophic state, conductivity, morphometry, and hydrology varied among reservoirs (Table 1). The trophic status of reservoirs was categorized (Forsberg and Ryding 1980) as oligotrophic (chlorophyll *a,* <3 mg/m^3), mesotrophic (3–7 mg/m^3), or eutrophic (≥ 8 mg/m^3). In three reservoirs, regulated water levels fluctuated 1.8–4.3 m annually but were stable in the other reservoirs. Water levels generally were at or near full pool when black bass initiated successful spawning and thus did not appear to be associated with spawning periodicity of either species (Greene 1995).

All six reservoirs lie within the Mobile and Chattahoochee river drainages and contain the Alabama spotted bass *M. p. henshalli* (MacCrimmon and Robbins 1975; Pierce and Van Den Avyle 1997). Florida largemouth bass *M. s. floridanus* composition ranged from 4% to 41% in these reservoirs that lie within the natural intergrade zone of both largemouth bass subspecies (Maceina and DiCenzo 1995). For this paper, we considered spotted bass to be the Alabama subspecies and the largemouth bass to be predominantly the northern subspecies *M. s. salmoides.*

Methods

During late June through late July 1993 and 1994, 12–20 fish samples were collected from each reservoir or site (Table 2) following Timmons et al. (1979). A 36.6-m × 2.4-m net (3-mm-bar mesh) encompassed a semicircle area of 0.02 ha. Shoreline sites throughout the reservoir were chosen based on shoreline depth, and obstacles and waterfront property that contained houses were avoided. Rotenone (5%) was applied (1 mg/L), all fish were collected for about 30 min, then the net was pulled toward the shore as a seine, and remaining fish were collected. During the 2-year pe-

TABLE 1.—Limnological, hydrological, and morphological characteristics of six Alabama reservoirs. Data were complied from Maceina et al. (1996), except those for embayments in Smith Lake, which were collected in this study. Limnological data (chlorophyll *a,* conductivity, and Secchi disk transparency) for other reservoirs were compiled by Maceina et al. (1996) from 1988 to 1993. Retention and mean depth are the historic values for these parameters. Regulated water level fluctuation (>1 m) was dictated by Alabama Power Company on Smith, Harris, and Weiss reservoirs. Percent spotted bass is the percentage of age-2 and older spotted bass of the total number of age-2 and older black bass pooled for both species. Data were complied from DiCenzo et al. (1995), Maceina et al. (1996), and from standardized electrofishing collections made at randomly chosen stations by the Alabama Department of Conservation and Natural Resources (unpublished data). In all, 962 largemouth bass and 910 spotted bass were collected.

Reservoir and site	Percent spotted bass (adults)	Chlorophyll *a* (mg/m^3)	Trophic state[a]	Secchi (m)	Retention (d)	Mean depth (m)	Conductivity (μS)	Regulated water level fluctuation (m)
Smith	74				435	20.0	38	4.3
Ryan's Creek		5	ME	1.46				
Sipsey River		4	ME	1.85				
Dam Forebay		1	OL	4.34				
Harding	29	7	ME	1.37	14	9.8	71	<1
Harris	62	5	ME	2.23	84	13.4	40	2.4
Jones Bluff	12	12	EU	0.97	5	5.8	96	<1
Lay	35	12	EU	1.10	9	6.7	141	<1
Weiss	4	27	EU	0.81	15	3.1	129	1.8

[a] ME = mesotrophic; OL = oligotrophic; EU = eutrophic.

riod, 79, 105, and 26 samples were collected from eutrophic, mesotrophic, and oligotrophic reservoirs (or sites), respectively. Largemouth bass and spotted bass less than 150 mm total length (TL) were identified in the field according to Ramsey and Smitherman (1972). Fish were then preserved in 70% ethanol and returned to the laboratory where each fish was measured (nearest mm TL) and weighed (nearest 0.1 g) and the sagittal otoliths were removed. We collected otoliths from fish in all reservoirs in 1993, but we only processed otoliths of fish from Harris, Smith, and Weiss reservoirs in 1994.

Otoliths were attached to microscope slides with thermoplastic cement, prepared in the sagittal plane (Miller and Storck 1982), and observed on an optical pattern recognition system (Jandel Video Analysis Software) at magnifications of 100–

TABLE 2.—Distribution of largemouth bass (LMB) and spotted bass (SPB) swim-up dates in six Alabama reservoirs, for which *N* is the number of fish, min and max are the earliest and latest recorded swim-up dates, and up-25th is upper 25th percentile for swim-up date. Years in which mean swim-up dates were significantly different ($P < 0.05$) between species within a reservoir are designated by an asterisk.

				Swim-up date			
Reservoir	Year	Species	*N*	Min	Up-25th	Mean	Max
Harris	1993*	LMB	28	24 Apr	3 May	8 May	19 May
		SPB	11	19 Apr	27 Apr	2 May	12 May
	1994*	LMB	27	5 Apr	20 Apr	26 Apr	9 May
		SPB	31	11 Apr	16 Apr	20 Apr	3 May
Smith	1993*	LMB	80	17 Apr	29 Apr	5 May	2 Jun
		SPB	56	17 Apr	23 Apr	29 Apr	14 May
	1994*	LMB	46	13 Apr	26 Apr	1 May	19 May
		SPB	123	9 Apr	22 Apr	27 Apr	24 May
Lay	1993	LMB	81	30 Mar	23 Apr	30 Apr	28 May
		SPB	45	12 Apr	23 Apr	27 Apr	16 May
Weiss	1993	LMB	42	20 Apr	2 May	8 May	26 May
		SPB	20	25 Apr	5 May	10 May	27 May
	1994	LMB	35	16 Apr	21 Apr	28 Apr	22 May
		SPB	31	12 Apr	24 Apr	2 May	16 May
Harding	1993*	LMB	30	11 Apr	15 Apr	23 Apr	13 May
		SPB	71	13 Apr	20 Apr	2 May	19 May
Jones Bluff	1993	LMB	89	30 Mar	17 Apr	23 Apr	15 May
		SPB	31	7 Apr	17 Apr	23 Apr	14 May

400×. Daily growth rings were counted twice from 678 fish, but not consecutively. If the two counts differed by three rings or less, the higher of the two counts was used. If counts differed by more than three rings, then a third count was made. When the difference between minimum and maximum counts was less than 10%, the mean of the three counts was used. If the three counts varied by more than 10%, the otolith was discarded and the second otolith was prepared.

Not all otoliths were prepared for estimating age. Up to 15 fish from each 10-mm size-group for each species and from each reservoir were aged. Ages of 72% and 81% of the largemouth bass and spotted bass used to describe swim-up distributions were estimated from otoliths. Remaining fish were assigned ages for 8 of 18 reservoir-species-years of data (9 reservoir years × 2 species) using discriminant function analysis with length as a discriminant function to predict age. Among the 8 reservoir-species-years where age was predicted using discriminant function analysis, length explained an average of 58% of the variability in age (range, 33–69%). Predicted ages were within ±5 d of the estimated age for 75% of largemouth bass and 73% of spotted bass. Mean daily growth rates (mm/d) were computed as: TL − 5 mm/age for largemouth bass and as TL − 6 mm/age for spotted bass, where 5 and 6 mm are the lengths at swim-up for largemouth bass and spotted bass, respectively (Miller and Storck 1982; DiCenzo and Bettoli 1995).

Swim-up dates were divided into three categories to provide species-specific comparisons of spawning periodicity and to relate variables to swim-up distributions. These included (1) initiation of swim-up or the oldest fish in the cohort, (2) the date when 25% of all fish had completed swim-up, and (3) mean date of swim-up. The relation between swim-up statistics and reservoir latitude was examined with correlation analysis. Mean swim-up dates were the same (one-way analysis of variance [ANOVA], $P > 0.05$) in the three regions of Smith Reservoir for each species, and these data were pooled to increase sample size in this reservoir where young black bass abundance was low.

In Smith Reservoir, biweekly (April–June) water samples (0.5 m below the surface) were collected for chlorophyll-*a* analysis, and Secchi disk transparency was recorded. Chlorophyll *a* was extracted, processed, and corrected for phaeophytin (APHA et al. 1985). Average chlorophyll *a,* Secchi disk transparency, and conductivity values were complied by Maceina et al. (1996) for data collected during April–October from 1988 to 1993.

Statistical *t*-tests were used to detect differences in mean swim-up date between black bass species for each reservoir year. Species differences in spawning duration were tested with analysis of covariance (ANCOVA) as ranges in swim-up were related to sample size. For each species, correlation analysis examined the strength of relations between density, biomass, and daily growth rates and the reservoir limnological and hydrologic variables listed in Table 1. Because reservoir limnological and hydrologic variables covaried, multiple regression and principal component analysis were used to detect which of these variables were the best predictors of density and biomass. For each species, differences in density, biomass, and daily growth rates among trophic states were tested with one-way ANOVA and the posthoc Student–Newman–Keuls mean separation test. For each trophic state, species differences in density, biomass, and daily growth rate were tested with a *t*-test. Finally, in Smith Reservoir, we examined if differences in chlorophyll *a* were associated with changes in black bass composition. One-way ANOVA and the Student–Newman–Keuls mean separation test were used to evaluate water quality differences in the three regions of Smith Reservoir.

Results

Spotted Bass and Largemouth Bass Spawning Distributions

Largemouth bass ($N = 549$) and spotted bass ($N = 539$) ranged from 29 to 103 mm TL and from 31 to 116 mm TL, respectively. Based on daily ring counts, largemouth bass ($N = 328$) ranged from 43 to 104 d in age and spotted bass ($N = 350$) were 43–101 d old. Successful hatching, based on surviving fish and daily ring counts, occurred during late March through early June each year (Table 2).

Time of swim-up varied between species for five of nine annual reservoir comparisons (Table 2). Spotted bass swam up significantly earlier than largemouth bass in Harris Reservoir in 1993 ($t = 2.44$, df = 37, $P < 0.05$) and 1994 ($t = 3.16$, df = 56, $P < 0.05$) and in Smith Reservoir in 1993 ($t = 4.22$, df = 134, $P < 0.01$) and 1994 ($t = 4.48$, df = 134, $P < 0.01$). However, in Harding Reservoir, largemouth bass swam up significantly earlier ($t = 5.07$, df = 99, $P < 0.01$). Average differences in mean swim-up dates varied from 4 to 10 d.

TABLE 3.—Correlation matrix of limnological, morphometric, and hydrologic variables to spotted bass and largemouth bass density (number/ha), biomass (g/ha), and growth (mm/d) among six Alabama reservoirs. All data were transformed to $\log_{10}$ values. Density and biomass data were for 16 reservoir–species–year combinations, including the three regions in Smith Reservoir, and 13 reservoir–species–year combinations of data were used to describe variables related to growth. Asterisks indicate significant differences: $P < 0.10$*, $P < 0.05$**, and $P < 0.01$***; NS is not significant.

	Largemouth bass			Spotted bass		
Variable	Density	Biomass	Growth	Density	Biomass	Growth
Chlorophyll *a*	0.72***	0.84***	0.81***	NS	NS	0.62**
Secchi disk transparency	−0.68***	−0.80***	−0.66**	NS	NS	NS
Retention	−0.62***	−0.71***	−0.77***	NS	−0.43*	−0.65**
Mean depth	−0.58**	−0.75***	−0.78***	NS	NS	−0.57**
Conductivity	0.58**	0.72***	0.87***	NS	0.58**	0.71***
Water level fluctuation	−0.56**	−0.57***	−0.60**	NS	−0.62**	−0.48*

The duration of successful spawning was slightly higher for largemouth bass than for spotted bass. The number of largemouth bass and spotted bass collected was positively correlated ($r = 0.58$ and 0.59, $N = 9$, $P < 0.10$) to the range of swim-up for each species. Among reservoirs, the range of swim-up varied from 25 to 59 d for largemouth bass and from 22 to 45 d for spotted bass. The slopes of the linear relations between swim-up range and number collected were not significantly different for largemouth bass and spotted bass ($F = 2.42$, df = 1,17, $P = 0.14$). However, the intercept for the swim-up range to number of fish collected was slightly higher for largemouth bass ($F = 3.35$, df = 1,17, $P < 0.10$). Thus, for a given number of fish collected, largemouth bass spawned over a slightly longer duration than spotted bass.

Factors Related to Abundance and Growth

Density and biomass of age-0 largemouth bass were greater in shallower, generally shorter-retention reservoirs with higher conductivities and chlorophyll *a* than in deeper, less productive reservoirs with generally longer retention and lower conductivities (Table 3). Age-0 spotted bass density and biomass were not associated with chlorophyll-*a* concentrations (Table 3). Higher biomass of spotted bass was weakly associated with shorter-retention reservoirs with more stable water characterized by higher ionic strength (Table 3).

Of the reservoir variables examined, chlorophyll *a* was consistently the strongest determinant of largemouth bass density and biomass. In multiple regression and principal-component analysis using reservoir limnological and hydrologic characteristics that all covaried, chlorophyll *a* explained the highest proportion of the variance and was the only significant ($P < 0.05$) predictor of largemouth bass density and biomass. For spotted bass, multiple regression and principal-component analysis could not statistically discern whether retention, conductivity, or water level fluctuation was a better predictor of biomass. None of the reservoir variables that we examined appeared associated with spotted bass density (Table 3).

Abundance of young largemouth bass increased over progressively higher trophic states and ranged in difference by an order of magnitude. Largemouth bass averaged 197, 108, and 21 fish/ha in eutrophic, mesotrophic, and oligotrophic systems, respectively, and significant differences were detected among each trophic state ($F = 18.10$, df = 2,207, $P < 0.01$). Similarly, largemouth bass biomass varied among eutrophic, mesotrophic, and oligotrophic water bodies and averaged 269, 88, and 17 g/ha, respectively ($F = 21.71$, df = 2,207, $P < 0.01$).

Biomass of spotted bass increased with trophic state, but a smaller difference was observed than with largemouth bass. Spotted bass biomass averaged 197, 139, and 92 g/ha in eutrophic, mesotrophic, and oligotrophic systems, and biomass was greater in eutrophic reservoirs than in the oligotrophic water body ($F = 3.39$, df = 2,207, $P < 0.05$). Spotted bass density did not vary as much as largemouth bass density among trophic states, but was highest (average = 149 fish/ha) in the mesotrophic reservoirs than in the oligotrophic section (average = 67 fish/ha) of Lewis Smith reservoir ($F = 3.14$, df = 2,207, $P < 0.05$). Density of both black bass species pooled averaged 318, 257, and 88 fish/ha in eutrophic, mesotrophic, and oligotrophic systems, respectively, and was significantly lower in the oligotrophic region of Smith Lake ($F = 16.99$, df = 2,207, $P < 0.01$). Biomass of black bass progressively declined from 466,

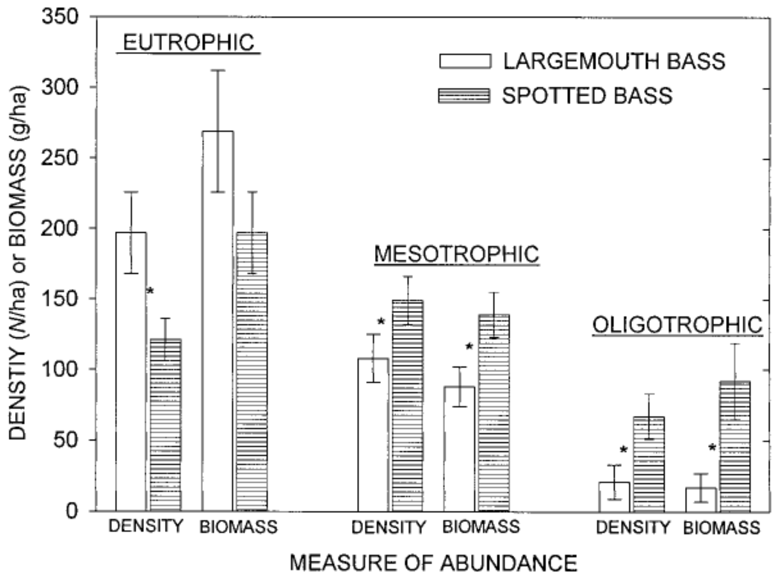

FIGURE 2.—Mean density and biomass of largemouth bass and spotted bass within trophic states in Alabama reservoirs or sites. Vertical lines represent ±SE; an asterisk indicates that mean values differed significantly ($P < 0.05$) between species.

228, and 109 g/ha in eutrophic, mesotrophic and oligotrophic systems ($F = 17.96$, df = 2,207, $P < 0.01$), respectively.

Predominance of age-0 spotted bass and largemouth bass varied among trophic states. Largemouth bass density was greater than spotted bass in eutrophic reservoirs ($t = 2.36$, df = 156 $P < 0.05$), but the density ($t = 3.08$, df = 208, $P < 0.01$) and biomass ($t = 3.48$, df = 208, $P < 0.01$) of spotted bass was higher than largemouth bass in mesotrophic reservoirs (Figure 2). Similarly, spotted bass density ($t = 3.89$, df = 50, $P < 0.01$) and biomass (($t = 4.02$, df = 50, $P < 0.01$) was greater than largemouth bass density and biomass in the oligotrophic section of Smith Lake (Figure 2). The percentage of age-0 spotted bass of both black bass pooled in each water body for each year was inversely associated with chlorophyll *a* ($r = -0.66$, $N = 9$, $P < 0.10$).

Black bass composition also varied spatially within Smith Reservoir and was associated with differences in water quality. Chlorophyll *a* was significantly lower ($F = 15.71$, df = 2,44, $P < 0.01$) and Secchi disk transparency significantly higher ($F = 37.25$, df = 2,44, $P < 0.01$) in the dam forebay than in the upstream tributary embayments, but chlorophyll-*a* concentrations and Secchi disk transparency were the same in both upper Ryan's Creek and Sipsey Arms (Table 1). Largemouth bass constituted only 15% and 24% of the total black bass density and biomass in the oligotrophic dam forebay compared with 42% and 44% in the mesotrophic Ryans Creek and Sipsey River embayments.

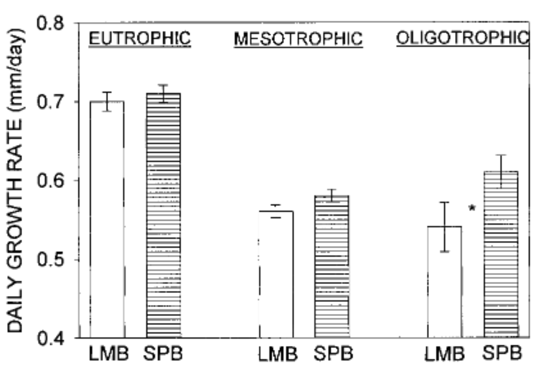

FIGURE 3.—Mean daily growth rates of largemouth bass (LMB) and spotted bass (SPB) by trophic state in Alabama reservoirs or sites. Vertical lines represent ±SE; an asterisk indicates that mean values differed significantly ($P < 0.10$) between species.

Largemouth bass and spotted bass daily growth rates were higher in more shallow, productive, short-retention reservoirs than in deeper, long-retention, less productive reservoirs (Table 3; Figure 3). Growth rates of largemouth bass ($F = 48.39$, df = 2, 325, $P < 0.01$) and spotted bass ($F = 47.70$, df = 2, 347, $P < 0.01$) were higher in eutrophic than in oligotrophic and mesotrophic reservoirs. Largemouth bass and spotted bass daily growth rates were similar in eutrophic (t = 0.41, df = 270, P = 0.68) and mesotrophic (t = 1.35, df = 358, P = 0.18) reservoirs (Figure 3). However, in the oligotrophic region of Smith Lake, spotted bass grew faster (t = 1.79, df = 44, P < 0.10) than largemouth bass (Figure 3). Species-specific differences in growth rates among trophic states were greatest for largemouth bass. This species grew 25–29% faster in eutrophic reservoirs than in oligotrophic and mesotrophic reservoirs, whereas spotted bass grew 16–22% faster in eutrophic reservoirs than in lower trophic states.

Discussion

Reservoir productivity during the first 2–3 months of life appeared to establish predominance of one species or codominance of both these black bass species in Alabama reservoirs. From our work, a higher proportion of spotted bass in Alabama were more likely to recruit to older ages than largemouth bass in lower-productivity reservoirs. Spotted bass swim-up occurred before that of largemouth bass in the two least-productive reservoirs, and young spotted bass were more abundant than largemouth bass in oligotrophic and mesotrophic reservoirs. In addition, young spotted bass grew faster than largemouth bass in an oligotrophic area of one of the study reservoirs. Abundance of age-0 largemouth bass was more strongly linked to trophic state than that of spotted bass. Hence, eutrophic conditions that were associated with other reservoir characteristics appeared to favor young largemouth bass. The relative abundance of age-0 spotted bass to largemouth bass was inversely associated with chlorophyll *a.* A similar pattern was observed for adult composition in these six study reservoirs.

Differences in age-0 largemouth bass density and biomass and the growth rates of both species appeared related to trophic state, but these differences also may be due to other reservoir morphometric, hydraulic, or limnological characteristics. However, for largemouth bass, chlorophyll *a* was consistently the strongest determinant of density, biomass, and growth.

Largemouth bass and spotted bass were equally abundant in oligo-mesotrophic regions of Cave Run Reservoir, Kentucky, but largemouth bass were three times more abundant than spotted bass in the upper eutrophic section (Buynak et al. 1989). In Smith Reservoir, we noted a similar response as age-0 spotted bass predominated oligotrophic regions of the reservoir, and upper mesotrophic regions supported nearly equal abundances of both species.

Biomass of both black bass species pooled was highest in eutrophic Alabama reservoirs due to the high density of largemouth bass and faster growth rates displayed by both species in these more productive systems. Oglesby (1977) and Jones and Hoyer (1982) found that primary production was positively correlated to fish yield in natural lakes and reservoirs. Axler et al. (1988) attributed the decline in the fisheries for largemouth bass and striped bass *Morone saxatilis* in Lake Mead, Nevada–Arizona, to nutrient reduction and a subsequent decline in trophic state. In Florida lakes, adult largemouth bass abundance was positively correlated to trophic state (Hoyer and Canfield 1996). Bayne et al. (1994) found that age-1 and older black bass abundance was higher in more eutrophic reservoirs than in an oligotrophic reservoir. Faster growth rates during the first year of life also increased the probability of first-year overwinter survival (Miranda and Hubbard 1994a, 1994b; Ludsin and DeVries 1997). Thus, the potential for higher black bass abundances in more productive water bodies appears to be established early in life.

We could not determine the mechanisms influencing trophic state interactions between age-0 largemouth bass and spotted bass. During the first year of life, food habits of these two species appear similar, as both initially consume zooplankton then convert to macroinvertebrates and later to fish (Heidinger 1975; Vogele 1975). We are not certain if spotted bass forage more effectively in clearer oligo-mesotrophic waters than largemouth bass, but this phenomenon warrants investigation. The higher abundance and faster growth of young spotted bass in deeper, lower production reservoirs may be due to behavioral adaptation to clear water or rocky substrate. Our results are consistent with longitudinal trophic gradients that typically occur in reservoirs (Wetzel 1990). Species-specific differences in early life characteristics along this gradient will probably affect black bass species composition and abundance.

These results have important implications for nutrient alteration and impact on phytoplankton as oligotrophication could favor young spotted bass and eutrophication of low-productivity water bodies may select for largemouth bass. In Alabama, growth of the Alabama spotted bass was slightly lower than largemouth bass from age 1 to age 5 (Maceina and DiCenzo 1995). Oligotrophication will probably reduce black bass growth rates, condition, and the size of fish caught by anglers (Maceina et al. 1996) and probably will increase the proportion of spotted bass in these fisheries. Alabama spotted bass rarely exceed 3 kg, whereas largemouth bass have the potential to reach greater sizes. Thus, changes in trophic status will modify black bass fisheries to the extent that different harvest regulations for these two species may be required (Buynak et al. 1991).

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References

APHA (American Public Health Association), American Water Works Association, and Water Pollution Control Federation. 1985. Standard methods for the examination of water and wastewater, 16th edition. APHA, Washington, D.C.

Axler, R. L., L. Paulson, P. Vaux, P. Solberger, and D. H. Baepler. 1988. Fish aid—the Lake Mead fertilization project. Lake and Reservoir Management 4(2):125–135.

Bayne, D. R., M. J. Maceina, and W. C. Reeves. 1994. Zooplankton, fish and sport fishing quality among four Alabama and Georgia reservoirs of varying trophic status. Lake and Reservoir Management 8: 153–163.

Buynak, G. L., L. E. Kornman, A. Surmont, and B. Mitchell. 1989. Longitudinal differences in electrofishing catches of black bass in Cave Run Lake, Kentucky. North American Journal of Fisheries Management 9:226–230.

Buynak, G. L., L. E. Kornman, A. Surmont, and B. Mitchell. 1991. Evaluation of a differential-harvest regulation for black bass in Cave Run Lake, Kentucky. North American Journal of Fisheries Management 11:277–284.

Copeland, J. R., and R. L. Noble. 1994. Movements by young-of-year and yearling largemouth bass and their implications for supplemental stocking. North American Journal of Fisheries Management 14: 119–124.

DiCenzo, V. J., and P. W. Bettoli. 1995. Verification of daily ring deposition in the otoliths of age-0 spotted bass. Transactions of the American Fisheries Society 124:633–636.

DiCenzo, V. J., M. J. Maceina, and W. C. Reeves. 1995. Factors related to growth and condition of the Alabama subspecies of spotted bass in reservoirs. North American Journal of Fisheries Management 15:794–798.

Forsberg, C., and S. O. Ryding. 1980. Eutrophication parameters and trophic state indices in 30 Swedish waste-receiving lakes. Archiv für Hydrobiologie 89: 189–207.

Greene, J. C. 1995. Factors influencing spawning periodicity, abundance, and growth of young-of-the-year largemouth bass and spotted bass in Alabama reservoirs. Master's thesis. Auburn University, Alabama.

Heidinger, R. C. 1975. Life history and biology of the largemouth bass. Pages 11–20 *in* H. Clepper, editor. Black bass biology and management. Sport Fishing Institute, Washington, D.C.

Hoyer, M. V., and D. E. Canfield, Jr. 1996. Largemouth bass and aquatic vegetation in Florida lakes: an empirical analysis. Journal of Aquatic Plant Management 34:23–32.

Jones, J. R., and M. V. Hoyer. 1982. Sportfish harvest predicted by summer chlorophyll-*a* concentrations in midwestern lakes and reservoirs. Transactions of the American Fisheries Society 111:176–179.

Kramer, R. H., and L. L. Smith, Jr. 1962. Formation of year classes in largemouth bass. Transactions of the American Fisheries Society 91:29–41.

Ludsin, S. A., and D. R. DeVries. 1997. First-year recruitment of largemouth bass: the interdependency of early life stages. Ecological Applications 7: 1024–1038.

MacCrimmon, H. R., and W. H. Robbins. 1975. Distribution of the black basses in North America. Pages 56–66 *in* H. Clepper, editor. Black bass biology and management. Sport Fishing Institute, Washington, D.C.

Maceina, M. J., and V. J. DiCenzo. 1995. Long-term genetic changes and growth of largemouth bass populations in Alabama public reservoirs. Alabama Department of Conservation and Natural Resources, Federal Aid in Fish and Wildlife Restoration, Project F-40, Study 22, Final Report, Montgomery.

Maceina, M. J., and five coauthors. 1996. Compatibility between water clarity and quality black bass and crappie fisheries in Alabama. Pages 296–305 *in* L. E. Miranda and D. R. DeVries, editors. Multidimensional approaches to reservoir fisheries management. American Fisheries Society, Symposium 16, Bethesda, Maryland.

Maceina, M. J., B. R. Murphy, and J. J. Isely. 1988. Factors regulating Florida largemouth bass stocking success and hybridization with northern largemouth bass in Aquilla Lake, Texas. Transactions of the American Fisheries Society 117:221–231.

Miller, S. J., and T. Storck. 1982. Daily growth rings in otoliths of young-of-the-year largemouth bass. Transactions of the American Fisheries Society 111: 527–530.

Miller, S. J., and T. Storck. 1984. Temporal spawning distribution of largemouth bass and young of the year growth, determined from daily growth rings.

Transactions of the American Fisheries Society 113: 571–578.

Miranda, L. E., and W. D. Hubbard. 1994a. Length-dependent winter survival and lipid composition of age-0 largemouth bass in Bay Springs Reservoir, Mississippi. Transactions of the American Fisheries Society 123:80–87.

Miranda, L. E., and W. D. Hubbard. 1994b. Winter survival of age-0 largemouth bass relative to size, predators, and shelter. North American Journal of Fisheries Management 14:790–796.

Ney, J. J. 1996. Oligotrophication and its discontents: effects of reduced nutrient loading on reservoirs fisheries. Pages 285–295 *in* L. E. Miranda and D. R. DeVries, editors. Multidimensional approaches to reservoir fisheries management. American Fisheries Society, Symposium 16, Bethesda, Maryland.

Oglesby, R. T. 1977. Relationships of fish yield to lake phytoplankton standing crop, production, and morphoedaphic factors. Journal of the Fisheries Research Board of Canada 34:2271–2279.

Pierce, P. C., and M. J. Van Den Avyle. 1997. Hybridization between introduced spotted bass and smallmouth bass in reservoirs. Transactions of the American Fisheries Society 126:939–947.

Ramsey, J. S., and R. O. Smitherman. 1972. Development of color pattern in pond-reared young of five Micropterus species of Southeastern U.S. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 25(1971): 348–356.

Sammons, S. M., L. G. Dorsey, P. W. Bettoli, and F. W. Fiss. 1999. Effects of reservoir hydrology on reproduction by largemouth bass and spotted bass in Normandy Reservoir, Tennessee. North American Journal of Fisheries Management 19:78–88.

Timmons, T. J., W. L. Shelton, and W. D. Davies. 1979. Sampling reservoir fish populations in littoral areas with rotenone. Proceedings of the Annual Conference Southeastern Association Fish and Wildlife Agencies 32(1978):474–485.

Vogele, L. E. 1975. The spotted bass. Pages 34–45 *in* H. Clepper, editor. Black bass biology and management. Sport Fishing Institute, Washington, D.C.

Wetzel, R. G. 1990. Reservoir ecosystems: conclusions and speculations. Pages 227–238 *in* K. W. Thorton, B. L. Kimmel, and F. E. Payne, editors. Reservoir limnology: ecological perspectives. Wiley, New York.

Yurk, J. J., and J. J. Ney. 1989. Phosphorus–fish community biomass relationships in southern Appalachian reservoirs: can lakes be too clean for fish? Lake and Reservoir Management 5:83–90.

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Recruitment of Largemouth Bass in Alabama Reservoirs: Relations to Trophic State and Larval Shad Occurrence

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Abstract.—Factors affecting recruitment of largemouth bass have frequently been evaluated, but few studies have assessed recruitment potential among a range for reservoirs of varying trophic states. We examined densities of larval threadfin shad *Dorosoma petenense* and gizzard shad *D. cepedianum* from March to July from nine Alabama impoundments. Using shoreline rotenone sampling and daily otolith rings, we estimated density, age, and growth of age-0 largemouth bass *Micropterus salmoides* in late June–July. Density and growth of larval gizzard shad, larval threadfin shad, and age-0 largemouth bass increased with chlorophyll *a* across impoundments. Duration of occurrence for larval gizzard shad and threadfin shad was positively related to chlorophyll *a.* Eutrophic reservoirs contained larval shad that were 40% or less of mean age-0 largemouth bass total length (i.e., the size at which they would probably be vulnerable to predation) in late June–July, whereas larval shad were generally not collected in late June or July in oligo–mesotrophic impoundments. Thus, piscivory on age-0 shad by age-0 largemouth bass was more likely to occur in eutrophic than in oligo–mesotrophic reservoirs. Eutrophic impoundments have high chlorophyll-*a* values and high larval threadfin shad and gizzard shad densities, and they may provide for greater recruitment of largemouth bass than oligo–mesotrophic impoundments.

Largemouth bass *Micropterus salmoides* support important recreational fisheries, particularly in the southeastern USA, where in 1991, about 50% of all freshwater anglers sought black basses *Micropterus* spp. (U. S. Department of the Interior 1996). Accordingly, a vast amount of research has focused on largemouth bass populations, and a recent emphasis has been on mechanisms affecting recruitment (Isely 1981; Gutreuter and Anderson 1985; Goodgame and Miranda 1993; Miranda and Hubbard 1994a, 1994b; Ludsin and DeVries 1997; Miranda and Pugh 1997).

As with most fishes, slight changes in growth or mortality during early life stages may substantially affect largemouth bass recruitment (Houde 1987). Abiotic factors affecting largemouth bass growth and mortality during early life may include weather patterns after spawning (Summerfelt 1975; Aggus 1979), water level fluctuations, system hydrology, and resulting habitat availability (Aggus and Elliot 1975; Shelton et al. 1979; Timmons et al. 1980; Timmons et al. 1981; Miranda et al. 1984; Ploskey 1986; Meals and Miranda 1991; Ploskey et al. 1996; Reinert et al. 1997). Biotic factors that can influence largemouth bass recruitment include availability and size of food (Houser and Rainwater 1975; Rainwater and Houser 1975; Shelton et al. 1979; Timmons et al. 1980; Ludsin and DeVries 1997) and timing of spawning of prey species and largemouth bass (Shelton et al. 1979; Adams and DeAngelis 1987; Stein et al. 1995; Ludsin and DeVries 1997).

Two important prey species for largemouth bass are gizzard shad *Dorosoma cepedianum* and threadfin shad *D. petenense,* which often contribute the majority of fish biomass in systems where they occur (Jenkins 1957, 1967). As such, recruitment dynamics of these two shad species may be extremely important to growth, survival, and recruitment success of piscivores, such as largemouth bass (Adams and DeAngelis 1987).

The timing of the appearance of larval shad *Dorosoma* spp. relative to that of largemouth bass spawning may affect age-0 largemouth bass growth and recruitment. Largemouth bass spawning typically occurs at about the same water temperature (12–20°C) as gizzard shad spawning (Shelton et al. 1982; Miller and Storck 1984; Allen

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and DeVries 1993; Ludsin and DeVries 1997) but at a lower temperature (and thus, earlier) than threadfin shad spawning (23–26°C; Johnson 1969; Allen and DeVries 1993). Further, age-0 gizzard shad often grow too large during their first summer to be consumed by age-0 largemouth bass, whereas age-0 threadfin shad may remain small enough in some years to be consumed by age-0 largemouth bass (Noble 1981; Heidinger 1983; Adams and DeAngelis 1987). Adams and DeAngelis (1987) developed a model of the relative spawning times of shad and largemouth bass and hypothesized that the highest growth rate of age-0 largemouth bass would occur when largemouth bass spawning was early in spring followed by a late spawn of shad. They suggested that environmental conditions that maximize the period between largemouth bass and shad spawning times would enhance the recruitment potential of age-0 largemouth bass population present during fall.

Previous studies have evaluated mechanisms affecting largemouth bass recruitment within populations, often comparing growth and survival of individuals in early hatched versus late-hatched cohorts. Although some investigators have evaluated adult largemouth bass populations in large multilake studies (Beamesderfer and North 1995; Maceina et al. 1996) or examined factors affecting recruitment in replicated pond experiments (Miranda and Hubbard 1994b; Ludsin and DeVries 1997), factors affecting age-0 largemouth bass abundance have seldom been evaluated on a multilake scale across a number of large systems (Hoyer and Canfield 1996; Reinert et al. 1997). Indeed, largemouth bass recruitment may vary across impoundments in which factors such as habitat availability, trophic state, larval shad abundance, timing of largemouth bass and prey fish spawning, and availability of food resources may differ greatly. Therefore, we evaluated factors related to age-0 largemouth bass density and growth rate during their first summer in nine Alabama impoundments.

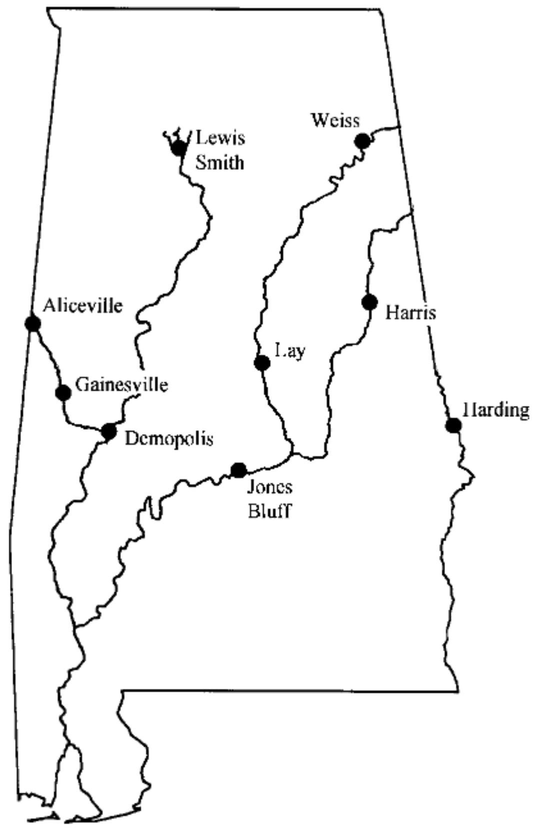

FIGURE 1.—Map of Alabama showing location of study reservoirs.

Methods

This study was conducted in nine Alabama reservoirs (Figure 1) during 1993 and 1994. The reservoirs were from four major river systems and differed in limnological and morphological characteristics (Table 1). The three major embayments of Lewis Smith Reservoir were considered separately because of differences in chlorophyll *a* and Secchi disk transparency (Table 1).

Sampling larval fish and water quality.—We sampled larval fish every 1 or 2 weeks (once per week in Harding, Harris, Weiss and Lay reservoirs) during mid-March through mid-July at each reservoir or site (i.e., sites from within Lewis Smith, reservoirs elsewhere). Larval fish were collected with a bow-mounted push net (2.0-m long, 0.75-m diameter, 500-μm mesh) pushed at 1.0–2.0 m/s for 10 min along the surface during daylight hours. A flowmeter was mounted in the mouth of the net for calculation of pushing speed and water volume sampled. On each sample date, three replicate samples were collected. All larvae were preserved in 95% ethanol, sorted by species, and counted. Larval gizzard shad and threadfin shad were identified to species and measured for total length (TL, mm) for a subsample of 30 fish/replicate, according to the procedures of Bulak (1985) and Santucci and Heidinger (1986). In conjunction with larval fish collections, we measured Secchi disk transparency (m) and collected water samples for analysis of planktonic chlorophyll-*a* concentrations at each reservoir or site. Chlorophyll-*a* concentrations

TABLE 1.—Limnological and morphological characteristics of our study reservoirs. Values are means of annual means from a reservoir database compiled by Maceina et al. (1996), with the exception of chlorophyll *a* and Secchi disk transparencies for the three sites in Lewis Smith Reservoir, where values are means of annual means collected from 1992 to 1994.

Reservoir or site	Chlorophyll *a* (mg/m^3)	Secchi disk transparency (m)	Mean depth (m)	Retention time (d)	Annual water level fluctuation (m)	Conductivity (μS)	Total alkalinity (mg/L)	Area (ha)
Lewis Smith			20.0	435	4.3	37	11	8,538
Dam Forebay	1	3.89						
Sipsey River	3	1.65						
Ryan Creek	4	1.30						
Harris	5	2.23	12.2	84	2.4	35	10	4,316
Harding	7	1.37	9.8	14	0.9	70	21	2,368
Gainesville	8	0.51	2.1	2	0.3	127	38	2,591
Aliceville	10	0.50	2.2	4	0.3	127	32	3,360
Demopolis	10	0.63	3.7	3	0.3	181	43	4,049
Jones Bluff	12	0.97	5.8	5	0.9	105	40	4,980
Lay	12	1.10	6.7	9	0.3	144	52	4,858
Weiss	27	0.81	3.1	15	1.8	137	53	11,297

were determined using the methods of APHA (1985).

Age-0 largemouth bass density and growth.—We collected age-0 largemouth bass using the shoreline rotenone technique of Timmons et al. (1978) during 1993 and 1994. During late June through July of both years, the reservoirs or sites were sampled using a 0.02-ha block net (3-mm-bar mesh). The net was anchored to shore, deployed in a semicircle, and anchored to the shore at the opposite end. Rotenone (1 mg/L) was applied, and all largemouth bass less than 150 mm TL were collected as they surfaced. The net was then pulled to shore and remaining fish were collected. The number of net sets per reservoir or site ranged from 12 to 20, but 12 or 13 nets were used at most reservoirs or sites each year. All age-0 largemouth bass were placed in 95% ethanol and returned to the laboratory, where they were measured (mm TL) and weighed (0.1 g); otoliths were removed to determine hatching date and growth rates (mm/d). In 1994, age-0 largemouth bass otoliths were collected only in Harris, Lewis Smith (all three sites), and Weiss reservoirs.

Otoliths were mounted on microscope slides with thermoplastic cement and prepared in the sagittal plane as described by Miller and Storck (1982). Otoliths of 15 largemouth bass from each 10-mm length-group were examined to determine age. Ages of other fish were extrapolated using a discriminant function, in which length and weight were used as predictors of age. All otoliths were observed on an Optical Pattern Recognition System (Jandel Video Analysis Software) at a magnification of 100–400×. Daily growth rings were counted twice (not consecutively) to increase precision. If the two counts differed by three rings or less, the higher of the two counts was used. If the counts disagreed by more than three rings, a third count was made. If the three counts varied by more than 10%, the otolith was discarded and the second otolith was prepared similarly and new counts made. A second reader randomly selected 10% of all otoliths and conducted counts for validation purposes. All counts by the two readers agreed within 10%. Mean daily growth rates (mm/d) were determined as:

$$(\mathrm{TL} - 5\ \mathrm{mm})/\,\mathrm{age}\ (\mathrm{d}), \tag{1}$$

as described by Miller and Storck (1982); the subtraction of 5 mm was used to correct for TL at swim-up.

Data analysis.—We used correlation analysis to examine trophic interactions across reservoirs or sites. Annual means were used from each year to test relations between annual mean chlorophyll-*a* concentrations and annual mean larval threadfin shad density. Where necessary, $\log_{10}$ transformations were used to homogenize the variance or linearize relations among variables.

We evaluated the potential for age-0 largemouth bass to consume larval gizzard shad and larval threadfin shad by comparing the mean length of larval gizzard shad and threadfin shad to the mean length of age-0 largemouth bass. Comparisons were limited to reservoirs from which larval shad were collected after 15 June of each year. Larval

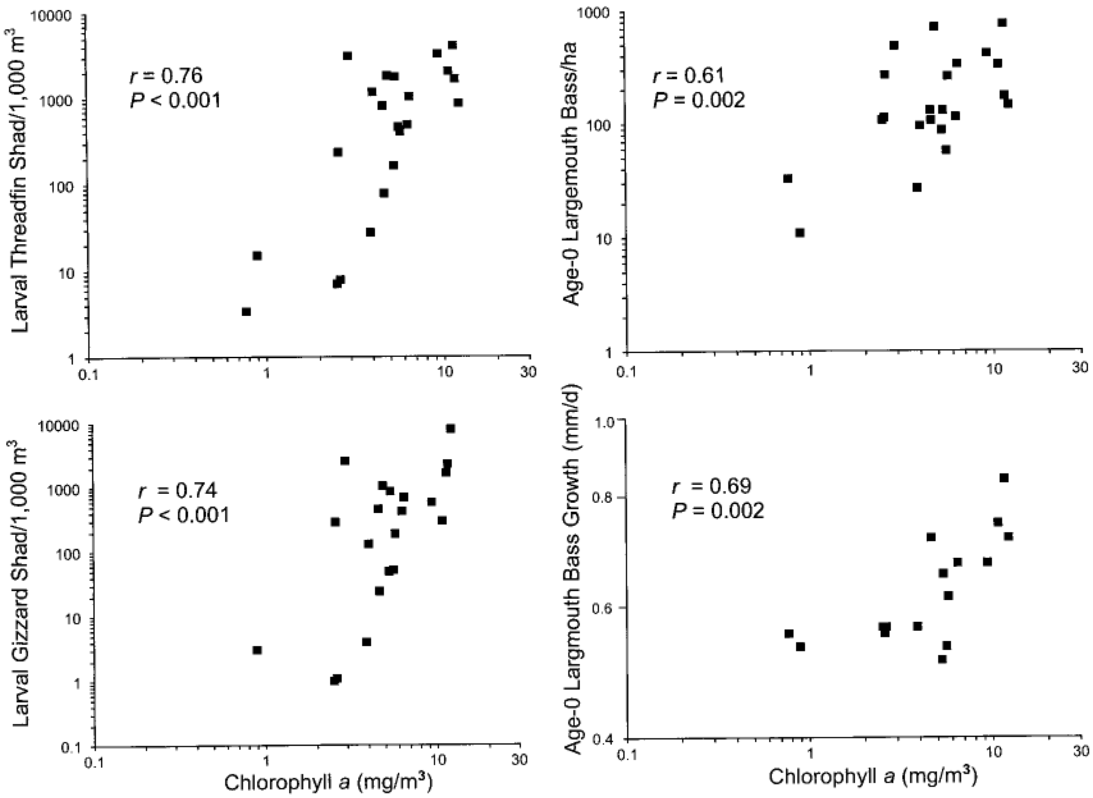

FIGURE 2.—Mean annual larval threadfin shad, gizzard shad, and age-0 largemouth bass densities and mean daily age-0 largemouth bass growth rate as a function of mean annual chlorophyll-*a* concentration (mg/m^3) for each reservoir or site in nine Alabama reservoirs, 1993–1994. Larval gizzard shad were not collected at the dam forebay site of Lewis Smith Reservoir in 1994.

shad of either species whose mean length was 40% or less of the total length of age-0 largemouth bass were considered potential food items (Shelton et al. 1979; Ludsin and DeVries 1997).

Results

Reservoirs varied in chlorophyll-*a* concentration, hydrology, and physical characteristics (Table 1). Based on chlorophyll-*a* values (Forsberg and Ryding 1980), lake trophic states ranged from oligotrophic (<3 mg/m^3) to eutrophic (8–40 mg/m^3). Reservoirs with high chlorophyll-*a* values generally had shorter retention and were shallower than reservoirs with low chlorophyll *a* (Table 1).

Reservoirs or sites with high chlorophyll *a* typically had higher larval shad abundance, and higher densities and more rapid growth rates of age-0 largemouth bass than reservoirs or sites with low chlorophyll *a.* For larval threadfin shad and gizzard shad, mean annual density increased with chlorophyll *a* (Figure 2). Age-0 largemouth bass density and growth rates also increased with chlorophyll *a* among reservoirs (Figure 2). Mean largemouth bass density and growth rates also were positively correlated with larval threadfin shad and gizzard shad densities (Figure 3).

Initiation of spawning for larval shad and mean swim-up date for largemouth bass were not related to trophic state. The first date of larval shad collection did not significantly differ between threadfin shad and gizzard shad ($t = -1.64$, df = 49, $P > 0.1$; two-tailed *t*-test, $\alpha = 0.05$). Additionally, the first date of larval shad collection was not correlated with chlorophyll *a* for either shad species (Figure 4). Likewise, mean largemouth bass swim-up date was not related to chlorophyll *a.*

The duration of larval shad presence was related to trophic conditions for both shad species. Total days of larval shad occurrence increased with chlorophyll *a* for both threadfin shad and gizzard shad (Figure 5). Larval shad were present later in summer in reservoirs or sites with high chlorophyll *a*

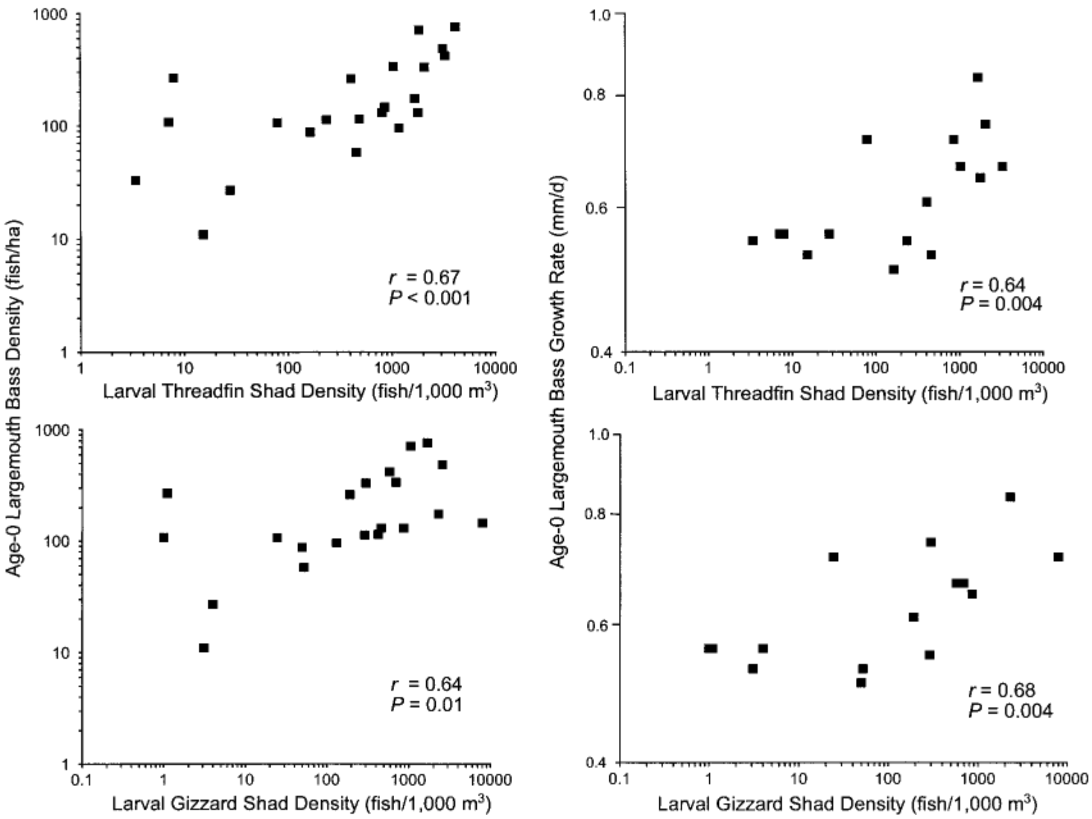

FIGURE 3.—Mean largemouth bass density and growth rate as functions of mean annual threadfin shad and gizzard shad densities. Larval gizzard shad were not collected at the dam forebay site of Lewis Smith Reservoir in 1994.

than in reservoirs with low chlorophyll *a.* For example, at reservoirs or sites with chlorophyll-*a* values of 5 mg/L or less, larval shad of both species were rarely collected in June, whereas in reservoirs with chlorophyll-*a* values of 8 mg/L or more, larval shad of both species were usually present after 15 June (Figure 5).

In reservoirs where larval shad of either species were present in late June–July, the size of larval gizzard shad and threadfin shad may have allowed them to serve as prey for age-0 largemouth bass. Larval shad were present in late June at six reservoirs in 1993 and five reservoirs in 1994 (Table 2). Mean length of larval shad was less than 40% of the mean length of largemouth bass, suggesting potential for piscivory on larval shad by age-0 largemouth bass when larvae were present after 15 June. We reiterate that in reservoirs with low chlorophyll *a,* larval gizzard shad and threadfin shad were not collected in late June or July, suggesting that larval shad of both species had either grown too large for capture in our larval push net or that the fish had perished.

Discussion

We found higher densities and more rapid growth of age-0 largemouth bass in reservoirs with high chlorophyll *a* and high larval gizzard shad and threadfin shad densities than in reservoirs with low chlorophyll *a* and low larval shad densities. DeVries et al. (1991) and DeVries and Stein (1992) found that larval threadfin shad and gizzard shad may reduce zooplankton abundance, and thereby survival of bluegills *Lepomis macrochirus* to the juvenile stage. Because bluegills migrate to littoral areas as juveniles (Werner 1967; Werner and Hall 1988) and serve as food for age-0 largemouth bass, larval gizzard shad and threadfin shad may indirectly reduce age-0 largemouth bass growth and recruitment by reducing larval bluegill survival and recruitment to littoral areas (DeVries et al. 1991; Stein et al. 1995). However, we found that reservoirs with high chlorophyll *a* and larval shad densities had more and faster growing age-0 largemouth bass than lakes with low chlorophyll *a* and low larval shad densities, which could increase largemouth bass recruitment.

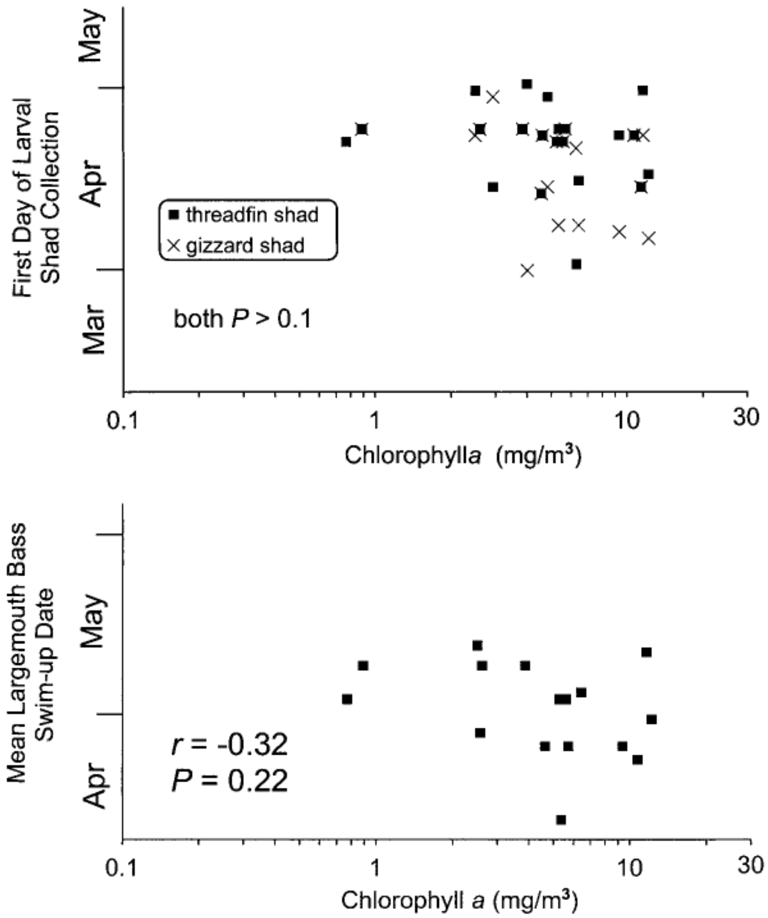

FIGURE 4.—First day of larval threadfin shad (squares) and gizzard shad (crosses) collections and mean largemouth bass swim-up date related to mean annual chlorophyll-*a* concentration. Larval gizzard shad were not collected at the dam forebay site of Lewis Smith Reservoir in 1994.

Largemouth bass recruitment to age 1 should be greater in reservoirs with higher chlorophyll *a* and high larval shad densities than in lakes with low chlorophyll *a* and low larval shad densities. Survival through the first winter appears to depend on fish size (Miller and Storck 1984; Maceina and Isely 1986; Miranda and Hubbard 1994b) and associated lipid reserves accumulated through fall (Keast and Eadie 1985; Miranda and Hubbard 1994a; Ludsin and DeVries 1997). Thus, the growth and density of age-0 largemouth bass that we quantified during summer may not have reflected recruitment to age 1 for these populations. Reservoirs with high larval shad densities generally had both higher densities and more rapid growth of age-0 largemouth bass than reservoirs or sites with low shad densities. Miranda and Hubbard (1994a) found that lipids of smaller (and presumably slower growing) age-0 largemouth bass declined more rapidly over the winter than lipids of larger age-0 fish in one reservoir and that large largemouth bass had higher overwinter survival than small fish. Ludsin and DeVries (1997) noted that large age-0 largemouth bass made an earlier switch to piscivory, had higher levels of body lipids, and had greater survival than small age-0 largemouth bass. Isely (1981) found a positive correlation between body length and lipid content for age-0 largemouth bass. Rapid growth and larger age-0 fish in reservoirs with high chlorophyll *a* and high larval shad densities is likely to have resulted in more lipid accumulation and higher survival of largemouth bass in our systems (as suggested by Ludsin and DeVries 1997).

Larval gizzard shad, larval threadfin shad, and age-0 largemouth bass densities increased with

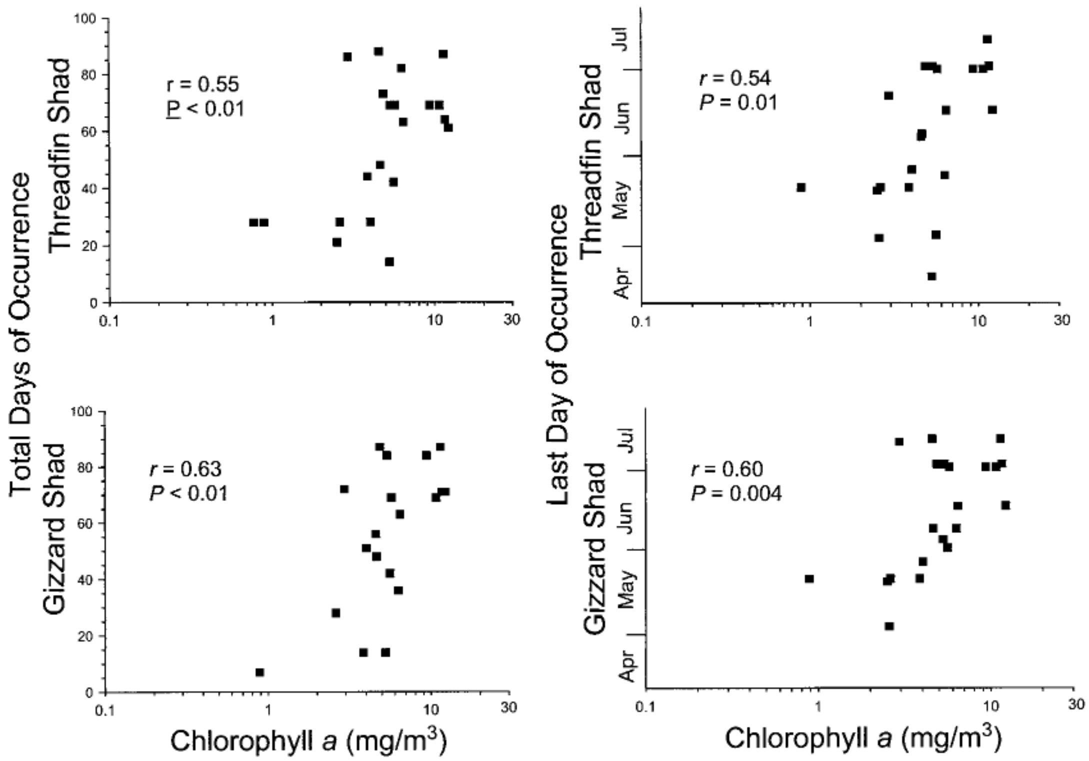

FIGURE 5.—Total days of occurrence and last day of occurrence for larval threadfin and gizzard shad related to mean annual chlorophyll-*a* concentration. Larval gizzard shad were not collected at the dam forebay site of Lewis Smith Reservoir in 1994.

trophic status. Adult (>age-1) threadfin shad and gizzard shad biomass typically increases with trophic conditions (Jenkins 1967; Siler et al. 1986; DiCenzo et al. 1996; Michaletz 1998). Gizzard shad and threadfin shad densities also increase with chlorophyll *a* early in life (Siler et al. 1986), and larval abundance of both shad species were positively related to trophic status in our reservoirs. Adult largemouth bass standing stock has increased with trophic conditions (Siler et al. 1986; Yurk and Ney 1989; Hoyer and Canfield 1996), but the relationship may be parabolic (Kautz 1982; Ney 1996), with reduced standing stock at extreme trophic levels (total phosphorus > 200 mg/m^3, Ney 1996). Age-0 largemouth bass density and growth increased linearly with chlorophyll *a* in this study, suggesting that recruitment potential was linear at long-term chlorophyll-*a* values ranging from 1 to 27 mg/m^3. Fishery managers may therefore expect stronger year-classes of largemouth bass in eutrophic impoundments than in oligo–mesotrophic impoundments.

We found prolonged occurrence of larvae of both shad species in reservoirs with high chlorophyll *a* compared with reservoirs with low chlorophyll *a,* which may affect the vulnerability of both shad species to age-0 or older predators. Using the same reservoirs as this study, DiCenzo et al. (1996) found that adult (≥age 1) gizzard shad populations in eutrophic reservoirs exhibited higher densities, slower growth, and smaller size structure than gizzard shad populations in oligo–mesotrophic reservoirs. Thus, gizzard shad growth rates in eutrophic impoundments may be density dependent (DiCenzo et al. 1996). Higher densities and prolonged occurrence of larval shad in eutrophic reservoirs compared with oligo–mesotrophic reservoirs suggests that reduced gizzard shad size structure could be manifested early in life. Increased vulnerability of gizzard shad to predation in eutrophic reservoirs (DiCenzo et al. 1996) may result from a combination of high densities and prolonged occurrence of larvae (e.g., extended recruitment into the stock) relative to oligo–mesotrophic reservoirs.

We did not document age-0 bass diets during June–July in this study, and the mechanisms causing rapid growth and high densities of age-0 large-

TABLE 2.—Mean total length (TL, mm) of age-0 largemouth bass and the proportion of the mean largemouth bass length exhibited by the mean length of larval threadfin shad and larval gizzard shad collected on or after 15 June of each year. Blanks indicate that no larval shad were collected after 15 June.

Reservoir or site	Largemouth bass TL (mm)	Proportion of largemouth bass length	
		Threadfin shad	Gizzard shad
1993 collection			
Lewis Smith			
Dam Forebay	45		
Sipsey River	46		
Ryan Creek	49		
Harris	41		
Harding	53		
Gainesville	53	0.22	0.27
Aliceville	60	0.28	0.30
Demopolis	61	0.11	0.20
Jones Bluff	44	0.13	0.12
Lay	52	0.34	0.38
Weiss	63	0.30	0.30
1994 collection			
Lewis Smith			
Sipsey River	46		
Ryan Creek	46		
Dam Forebay	45		
Harris	46		
Harding	48		
Gainesville	47	0.17	0.17
Aliceville	48	0.16	0.17
Demopolis	55	0.15	0.17
Jones Bluff	57	0.15	
Lay	44		
Weiss	59	0.19	0.17

mouth bass in eutrophic reservoirs were not identified. However, given the prolonged occurrence of larvae of both shad species in eutrophic reservoirs, we surmise that piscivory on age-0 shad by age-0 largemouth bass would be more likely to occur in eutrophic reservoirs than in oligo–mesotrophic reservoirs in this study. Previous authors have found, however, that age-0 largemouth bass less than 100 mm TL do not prey on age-0 gizzard shad or age-0 threadfin shad in summer (Timmons et al. 1980; Bettoli et al. 1992), with some exceptions (Pasch 1975; Miller and Storck 1984). The importance of age-0 shad in age-0 largemouth bass diets may increase in the fall as largemouth bass surpass 100 mm TL (Miller and Storck 1984; Bettoli et al. 1992; Miranda and Pugh 1997), but gizzard shad may also outgrow predation by age-0 largemouth bass by fall (Phillips et al. 1995). The importance of age-0 shad to age-0 largemouth bass diets during summer and fall may be related to temporal spawning patterns of each species earlier in the summer (Adams and DeAngelis 1987).

Our observations differ from the predictions of Adams and DeAngelis (1987), who suggested that age-0 largemouth bass should grow more rapidly when early largemouth bass spawning coincides with late spawning of shad. In this study, we found no differences in initial occurrence of larval threadfin shad and gizzard shad among reservoirs, but spawning duration (as indicated by duration of occurrence of larval threadfin shad and gizzard shad) increased with trophic conditions. Thus, in our systems, duration of larval shad occurrence rather than initiation of spawning was related to the potential for piscivory on age-0 gizzard shad and threadfin shad by age-0 largemouth bass.

By examining a number of reservoirs that differed in trophic state, larval shad densities, and temporal occurrences, we were able to identify factors related to largemouth bass recruitment on a broad scale (i.e., across drainages). Previous authors have examined recruitment of age-0 largemouth bass within populations (Aggus and Elliot 1975; Timmons et al. 1980; Timmons et al. 1981; Miller and Storck 1984; Maceina and Isely 1986; Miranda and Hubbard 1994a; Phillips et al. 1995; Ploskey et al. 1996; Miranda and Pugh 1997). We detected differences in the recruitment potential of largemouth bass populations among reservoirs, which may yield insight into the types of reservoirs that are likely to produce strong annual recruitment of largemouth bass. However, results from this study are correlative and, therefore, cannot identify mechanisms that caused rapid growth and high density of age-0 largemouth bass. We encourage efforts to quantify causal mechanisms affecting recruitment among systems. We conclude that eutrophic impoundments with high chlorophyll *a* and high larval shad densities may provide higher recruitment of largemouth bass than oligo–mesotrophic impoundments with low chlorophyll *a* and lower larval shad densities.

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References

Adams, S. M., and D. L. DeAngelis. 1987. Indirect effects of early bass–shad interactions on predatory population structure and food web dynamics. Pages 103–117 *in* W. C. Kerfoot and A. Sih, editors. Predation: direct and indirect impacts on aquatic communities. University Press of New England, Hanover, New Hampshire.

Aggus, L. R. 1979. Effects of weather on freshwater fish predator–prey dynamics. Pages 47–56 *in* H. Clepper, editor. Predator–prey systems in fisheries management. Sport Fishing Institute, Washington, D.C.

Aggus, L. R., and G. V. Elliot. 1975. Effects of cover and food on year-class strength of largemouth bass. Pages 317–322 *in* H. Clepper, editor. Black bass biology and management. Sport Fishing Institute, Washington, D.C.

Allen M. S., and D. R. DeVries. 1993. Spatial and temporal heterogeneity of larval shad in a large impoundment. Transactions of the American Fisheries Society 122:1070–1079.

APHA (American Public Health Association). 1985. Standard methods for the examination of water and wastewater, 16th edition. APHA, Washington, D.C.

Beamesderfer, R. C. P., and J. A. North. 1995. Growth, natural mortality, and predicted response to fishing for largemouth bass and smallmouth bass populations in North America. North American Journal of Fisheries Management 15:688–704.

Bettoli, P. W., M. J. Maceina, R. L. Noble, and R. K. Betsill. 1992. Piscivory in largemouth bass as a function of aquatic macrophyte abundance. North American Journal of Fisheries Management 12: 509–516.

Bulak, J. S. 1985. Distinction of larval blueback herring, gizzard shad, and threadfin shad from the Santee–Cooper drainage, South Carolina. Journal of the Elisha Mitchell Scientific Society 101:177–186.

DeVries, D. R., and R. A. Stein. 1992. Complex interactions between fish and zooplankton: quantifying the role of an open-water planktivore. Canadian Journal of Fisheries and Aquatic Sciences 49:1216–1227.

DeVries, D. R., R. A. Stein, J. G. Miner, and G. G. Mittelbach. 1991. Stocking threadfin shad: consequences for young-of-year fishes. Transactions of the American Fisheries Society 120:368–381.

DiCenzo, V. J., M. J. Maceina, and M. R. Stimpert. 1996. Relations between trophic state and gizzard shad population characteristics in Alabama Reservoirs. North American Journal of Fisheries Management 16:888–895.

Forsberg, C., and S. O. Ryding. 1980. Eutrophication parameters and trophic state indices in 30 Swedish waste-receiving lakes. Archives für Hydrobiologie 89:189–207.

Goodgame, L. S., and L. E. Miranda. 1993. Early growth and survival of age-0 largemouth bass in relation to parental size and swim-up time. Transactions of the American Fisheries Society 122:131–138.

Gutreuter, S. J., and R. O. Anderson. 1985. Importance of body size to the recruitment process in largemouth bass populations. Transactions of the American Fisheries Society 114:317–327.

Heidinger, R. C. 1983. Life history of gizzard shad and threadfin shad as it relates to the ecology of small lake fisheries. Pages 1–13 *in* D. Bonneau and G. Radonski, editors. Pros and cons of shad. Proceedings of small lakes management workshop. Iowa Conservation Commission, Des Moines.

Houde, E. D. 1987. Fish early life dynamics and recruitment variability. Pages 17–29 *in* R. D. Hoyt, editor. 10th annual larval fish conference. American Fisheries Society, Symposium 2, Bethesda, Maryland.

Houser, A., and W. C. Rainwater. 1975. Production of largemouth bass in Beaver and Bull Shoals lakes. Pages 310–316 *in* H. Clepper, editor. Predator–prey systems in fisheries management. Sport Fishing Institute, Washington, D.C.

Hoyer, M. V., and D. E. Canfield, Jr. 1996. Largemouth bass abundance and aquatic vegetation in Florida lakes: an empirical analysis. Journal of Aquatic Plant Management 34:23–32

Isely, J. J. 1981. Effects of water temperature and energy reserves on overwinter mortality in young-of-the-year largemouth bass (*Micropterus salmoides*). Master's thesis. Southern Illinois University, Carbondale.

Jenkins, R. M. 1957. The effect of gizzard shad on the fish population of a small Oklahoma lake. Transactions of the American Fisheries Society 85:58–74.

Jenkins, R. M. 1967. The influence of some environmental factors on standing crop and harvest of fishes in U.S. reservoirs. Pages 298–321 *in* Reservoir fisheries resources symposium. American Fisheries Society, Southern Division, Reservoir Committee, Bethesda, Maryland.

Johnson, J. E. 1969. Reproduction, growth, and population dynamics of threadfin shad, *Dorosoma petenense* (Gunther), in central Arizona reservoirs. Doctoral dissertation. Arizona State University, Tempe.

Kautz, R. S. 1982. Effects of eutrophication on the fish communities of Florida lakes. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 34(1980):67–80.

Keast, A., and J. M. Eadie. 1985. Growth depensation in year-0 largemouth bass: the influence of diet. Transactions of the American Fisheries Society 114: 204–213.

Ludsin, S. A., and D. R. DeVries. 1997. First-year recruitment of largemouth bass: the inter-dependency of early life stages. Ecological Applications 9: 1024–1038.

Maceina, M. J., and five coauthors. 1996. Compatibility

between water clarity and quality black bass and crappie fisheries in Alabama. Pages 296–305 *in* L. E. Miranda and D. R. DeVries, editors. Multidimensional approaches to reservoir fisheries management. American Fisheries Society, Symposium 16, Bethesda, Maryland.
Maceina, M. J., and J. J. Isely. 1986. Factors affecting growth of an initial largemouth bass year class in a new Texas reservoir. Journal of Freshwater Ecology 3:485–492.
Meals, K. O., and L. E. Miranda. 1991. Variability in abundance of age-0 centrarchids among littoral habitats of flood control reservoirs in Mississippi. North American Journal of Fisheries Management 11: 298–304.
Michaletz, P. H. 1998. Population characteristics of gizzard shad in Missouri reservoirs and their relation to reservoir productivity, mean depth, and sport fish growth. North American Journal of Fisheries Management 18:114–123.
Miller, S. J., and T. Storck. 1982. Daily growth rings in otoliths of young-of-year largemouth bass. Transactions of the American Fisheries Society 111:527–530.
Miller, S. J., and T. Storck. 1984. Temporal spawning distribution of largemouth bass and young-of-year growth, determined from daily otolith rings. Transactions of the American Fisheries Society 113:571–578.
Miranda, L. E., and W. D. Hubbard. 1994a. Length-dependent winter survival and lipid composition of age-0 largemouth bass in Bay Springs Reservoir, Mississippi. Transactions of the American Fisheries Society 123:80–87.
Miranda, L. E., and W. D. Hubbard. 1994b. Winter survival of age-0 largemouth bass relative to size, predators, and shelter. North American Journal of Fisheries Management 14:790–796.
Miranda, L. E., and L. L. Pugh. 1997. Relations between vegetation coverage and abundance, size and diet of juvenile largemouth bass during winter. North American Journal of Fisheries Management 17: 601–610.
Miranda, L. E., W. L. Shelton, and T. D. Bryce. 1984. Effects of water level manipulation on abundance, mortality, and growth of young-of-year largemouth bass in West Point Reservoir, Alabama–Georgia. North American Journal of Fisheries Management 4:314–320.
Ney, J. J. 1996. Oligotrophication and its discontents: effects of reduced nutrient loading on reservoir fisheries. Pages 285–295 *in* L. E. Miranda and D. R. DeVries, editors. Multidimensional approaches to reservoir fisheries management. American Fisheries Society, Symposium 16, Bethesda, Maryland.
Noble, R. L. 1981. Management of forage fishes in impoundments in the southern United States. Transactions of the American Fisheries Society 110:738–750.
Pasch, R. W. 1975. Some relationships between food habits and growth of largemouth bass in Lake Blackshear, Georgia. Proceedings of the Annual Conference Southeastern Association of Game and Fish Commissioners 28(1974):307–321.
Phillips, J. M., J. R. Jackson, and R. L. Noble. 1995. Hatching date influence on age-specific diet and growth of age-0 largemouth bass. Transactions of the American Fisheries Society 124:370–379.
Ploskey, G. R. 1986. Effects of water-level changes on reservoir ecosystems with implications for fisheries management. Pages 86–97 *in* G. E. Hall and M. J. Van Den Avyle, editors. Reservoir fisheries management: strategies for the 80's. American Fisheries Society, Southern Division, Reservoir Committee, Bethesda, Maryland.
Ploskey, G. R., J. M. Nestler, and W. M. Bivin. 1996. Predicting black bass reproductive success from Bull Shoals Reservoir hydrology. Pages 422–441 *in* L. E. Miranda and D. R. DeVries, editors. Multidimensional approaches to reservoir fisheries management. American Fisheries Society, Symposium 16, Bethesda, Maryland.
Rainwater, W. C., and A. Houser. 1975. Relation of physical and biological variables to black bass crops. Pages 306–309 *in* H. Clepper, editor. Predator–prey systems in fisheries management. Sport Fishing Institute, Washington, D.C.
Reinert, T. R., G. R. Ploskey, and M. J. Van Den Ayvle. 1997. Effects of hydrology on black bass reproductive success in four southeastern reservoirs. Proceedings of the Annual Conference Southeastern Association of Fish and Wildlife Agencies 49(1995):47–57.
Santucci, V. J., Jr., and R. C. Heidinger. 1986. Use of total myomere numbers to differentiate larvae of threadfin and gizzard shad. Transactions of the Illinois State Academy of Science 79:197–202.
Shelton, W. L., W. D. Davies, T. A. King, and T. J. Timmons. 1979. Variations in growth of the initial year class of largemouth bass in West Point Reservoir, Alabama and Georgia. Transactions of the American Fisheries Society 108:142–149.
Shelton, W. L., C. D. Riggs, and L. G. Hill. 1982. Comparative reproductive biology of the threadfin and gizzard shad in Lake Texoma, Oklahoma–Texas. Pages 47–51 *in* C. F. Bryan, J. V. Conner, and F. M. Truesdale, editors. The fifth annual larval fish conference. Louisiana Cooperative Fisheries Research Unit and the School of Forestry and Wildlife Management, Louisiana State University, Baton Rouge.
Siler, J. R., W. J. Foris, and M. C. McInerny. 1986. Spatial heterogeneity in fish parameters within a reservoir. Pages 122–136 *in* G. E. Hall and M. J. Van Den Ayvle, editors. Reservoir fisheries management: strategies for the 80's. Reservoir Committee, Southern Division American Fisheries Society, Bethesda, Maryland.
Stein, R. A., D. R. DeVries, and J. M. Dettmers. 1995. Food-web regulation by a planktivore: exploring the generality of the trophic cascade hypothesis. Canadian Journal of Fisheries and Aquatic Sciences 52:2518–2526.
Summerfelt, R. C. 1975. Relationship between weather and year-class strength of largemouth bass. Pages

166–174 *in* H. Clepper, editor. Black bass biology and management. Sport Fishing Institute, Washington, D.C.

Timmons, T. J., W. L. Shelton, and W. D. Davies. 1978. Sampling reservoir fish populations in littoral areas with rotenone. Proceedings of the Annual Conference Southeastern Association Fish and Wildlife Agencies 32(1978):474–485.

Timmons, T. J., W. L. Shelton, and W. D. Davies. 1980. Differential growth of largemouth bass in West Point Reservoir, Alabama–Georgia. Transactions of the American Fisheries Society 109:176–186.

Timmons, T. J., W. L. Shelton, and W. D. Davies. 1981. Early growth and mortality of largemouth bass in West Point Reservoir, Alabama–Georgia. Transactions of the American Fisheries Society 110:489–494.

U.S. Department of the Interior. 1996. Black bass fishing in the U.S. Report 91-4, Addendum to 1991 National Survey of Fishing, Hunting, and Wildlife-Associated Recreation. U.S. Fish and Wildlife Service, Division of Federal Aid, Washington, D.C.

Werner, R. G. 1967. Intralacustrine movements of bluegill fry in Crane Lake, Indiana. Transactions of the American Fisheries Society 96:416–420.

Werner, W. W., and D. J. Hall. 1988. Ontogenetic habitat shifts in bluegill: the foraging rate-predation risk trade-off. Ecology 69:1352–1366.

Yurk, J. J., and J. J. Ney. 1989. Phosphorus–fish community biomass relationships in southern Appalachian reservoirs: can lakes be too clean for fish? Lake and Reservoir Management 5:83–90.

GEORGIA DNR
Wildlife Resources Division
Fisheries Section

LAKE BURTON TROUT FISHERY

To fish for trout on Lake Burton requires a fishing license. A trout stamp is also needed if you plan to keep any trout that you catch.

For more information about fishing in Georgia, visit our website at www.gofishgeorgia.com

EXPERT TIPS FOR FISHING LAKE BURTON IN SPRING, SUMMER, FALL AND WINTER

Lake Burton is a 2,785-acre reservoir located between Clayton and Hiawassee that supports Georgia's only reservoir trout fishery.

There are three factors in Lake Burton that few southern impoundments possess, which enable it to support trout:

(1) a bountiful supply of cool water,
(2) sufficient dissolved oxygen, and
(3) suitable forage.

The surrounding mountain streams flowing into the lake provide a continuous supply of cool, well-oxygenated water, and blueback herring provide the forage needed for trout to grow fast and big. Couple these things with an annual stocking program by GA-DNR and you have all the ingredients for a great reservoir trout fishery.

Spring Fishing Tips . . . . .

Spring is a major transition period for trout in Lake Burton because water temperatures are warming rapidly, but are still cool enough to allow trout to roam freely throughout the lake.

The key to locating and catching trout during this period is finding their favorite food—**Blueback Herring**. In April and May, blueback herring are spawning on rocky shorelines around the main lake and in the tributary streams. Lures that imitate a blueback herring, like a Pearl Super Fluke or Zara Spook or Shad Rap are effective this time of year. Find spawning herring and hungry trout will likely be near by.

A second approach is to troll crank baits in silver or crayfish patterns near the mouth of the major tributaries. Moccasin Cove, adjacent to the Trout Hatchery, is the best one.

For bank anglers, the docks adjacent to the Moccasin Creek boat ramp, which is behind the hatchery, offer a chance to catch a trout, too. Small spinners and crankbaits can be effective during the twilight hours.

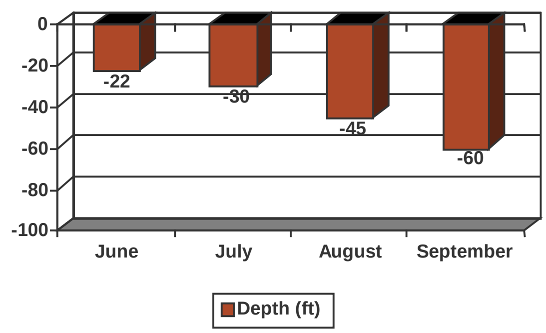
Lake Burton Record
11 pound, 2 oz Brown Trout

Summer Fishing Tips . . . . .

During the hot summer months, surface temperatures become too warm for trout, so they seek the cooler refuge of deeper waters. The migration to deeper water actually improves your chances of success because fish will become more concentrated in the lower lake.

There are three keys to catching trout during the summer—depth, bait selection, and trolling. Proper depth is the first and most important key ingredient.

Depth of Burton Lake Trout in Summer



Trout move to increasingly deeper water as summer progresses. The graph above indicates the typical depth range of trout during the summer. For trolling, downriggers are a useful tool in getting baits to the proper depth. For still fishing, slip floats will ensure you are at the proper depth.

Bait selection is the second key. Trolling spoons, such as the Krocodile spoon, Doctor spoon or Sutton spoon, and live bait, preferably blueback herring or medium shiners, are effective during the summer months. For still fishing, live shiners or nightcrawlers are your best choices.

Blue Marlin Krocodile spoon

Finally, cover a lot of water by trolling your baits at the critical depths. There are no submerged trees to snag your lures, so keep moving (2-3 mph), especially on the lower half of the lake.

Fall Fishing Tips . . . . .

As the leaves change into their fall colors, brown trout will migrate into the coves of Lake Burton.

This is a great time to catch big fish from the shoreline. Small spinners, like Rooster Tails and Mepps Spinners, as well as small Rapalas are effective baits to cast from the shoreline.

Anglers may also enjoy good success fishing with minnows or nightcrawlers on the boat docks adjacent to the boat ramp behind the Trout Hatchery.

Boating anglers should watch for signs of surface feeding fish, especially in Moccasin Cove. Small spoons, like a contrasting blue/silver Little Cleo, and surface plugs are effective lures this time of year.

Winter Fishing Tips . . . . .

Winter fishing on Lake Burton is not for the cold-natured angler, but a sunny afternoon can provide good trout fishing conditions.

During cold weather, trout will follow blueback herring into pockets of warmer water. These pockets occur along the face of Burton Dam as the afternoon sun radiates heat off the concrete wall.

The mouth of tributary streams also hold trout and bluebacks during the winter. At the dam, fishing with live herring or shiners at depths from 15 to 30 feet works best. In the coves, slowly troll either live bait or Shad Raps.

Floating Slip Rig

WEATHER

Best Water Temperatures for Brown Trout Fishing (Guide)

By Eric Matechak August 15, 2023

Water temperature is the most crucial thing to consider when setting off to fish for brown trout, and it can decide how you should approach your angling to net the most fish.

For brown trout fishing, water temperatures between 50 to 60 degrees Fahrenheit (10 to 15.5 degrees Celsius) are ideal, with the best fishing conditions usually found when the water temperature is around 55 to 57 degrees Fahrenheit (12.5 to 14 degrees Celsius).

Water Temperature (°F)	Quality of Brown Trout Fishing
Below 40°	Less active, slow movements, may be lethargic.
41-50°	Becoming more active, moving to shallower areas.
51-60°	Active, feeding more, actively searching for food.
61-68°	Very active, actively feeding, often near structures.
69-73°	Active and feeding, actively chasing prey.
Above 74°	Becoming less active, seeking cooler areas.

While even seasoned fishermen might tell you that brown trout will bite at any temperature (which isn't entirely wrong), there are certain things to consider in how differences in temperature and sudden shifts can change brown trout feeding habits.

This article will cover the ideal temperatures for brown trout fishing, emphasizing typical behavior at given temperature ranges, what baits and lures to use for different conditions, and how brown trout react to storms and sudden changes in water temperature.

Brown Trout Fishing by Water Temperature

Below 40°

Brown trout become less active and feed less frequently when the water temperature is below 40 degrees Fahrenheit (4.4 degrees Celsius). Here's what you need to know:

- Brown trout tend to move to deeper, slower-moving areas like deep pools or slower sections of the river to conserve energy.

- They focus on small aquatic insects and other small organisms present year-round in the water.
- Since their activity levels are lower, using slow and subtle techniques is best. Nymph flies imitating small insects like midges and stoneflies are effective.

41-50°

Brown trout are still active and looking for food when the water temperature is between 41 and 50 degrees Fahrenheit (5 to 10 degrees Celsius). Here's what you need to know:

- In cooler water around 41-45 degrees Fahrenheit, brown trout often stay in deeper areas like pools and slower currents. They focus on insects like stoneflies and midges. Using nymph flies that imitate these insects underwater can be effective.
- As the water warms towards 46-50 degrees Fahrenheit, brown trout might move to slightly shallower areas and feed more actively. They could still be eating nymphs and larger insects. Presenting your flies using techniques like dead-drifting or slow retrieves can work well.

51-60°

Brown trout are usually active and eager to eat when the water temperature is between 51 and 60 degrees Fahrenheit (10.5 to 15.5 degrees Celsius). They can be found in different parts of the river:

- In cooler water around 51-55 degrees Fahrenheit, brown trout may be in faster areas like riffles and runs, searching for insects like mayflies and caddisflies. Dry flies resembling these insects on the water's surface can be effective.
- As the water warms towards 56-60 degrees Fahrenheit, brown trout might move to deeper pools and shady spots to stay comfortable. They could focus on larger insects and small fish. Using nymph flies that look like these food sources underwater can work well.

61-68°

Brown trout are usually active and continue feeding in water temperatures ranging from 61 to 68 degrees Fahrenheit (16 to 20 degrees Celsius). They can be found in different parts of the river, depending on the specific temperature:

- In cooler water closer to 61-65 degrees Fahrenheit, brown trout might stay in faster-moving areas like riffles and runs, looking for insects like mayflies and caddisflies. Dry flies that imitate these insects on the water's surface can be effective.
- As the water warms towards 66-68 degrees Fahrenheit, brown trout might move to deeper pools and shaded spots to stay comfortable. They could focus on larger insects and small fish. Using nymph flies that mimic these food sources underwater can work well.

69-73°

In water temperatures below 69-73 degrees Fahrenheit (20.5-22.8 degrees Celsius), brown trout remain active and continue to feed, although their behavior can change based on the specific temperature:

- In cooler temperatures closer to 69 degrees Fahrenheit, brown trout might stay in faster-moving areas like riffles and runs, where the water is well-oxygenated. They feed on insects like mayflies and caddisflies. Dry flies that imitate these insects on the water's surface can be effective.
- As the water warms towards 73 degrees Fahrenheit, brown trout might seek out deeper pockets and shaded spots to stay comfortable. They can still be found in runs and pools, focusing on aquatic insects and small fish. Nymph flies that resemble these food sources can work well, presented near the riverbed.

Above 74°

Brown trout become more cautious and selective about feeding when the water temperature goes above 74 degrees Fahrenheit (23.3 degrees Celsius). Here's what you need to know:

- Brown trout might move to cooler, shaded areas like under overhanging trees or deeper pools to escape the warmer water.
- They could focus on finding active insects on the surface, like grasshoppers or other terrestrial bugs.
- Brown trout tend to feed more actively during the cooler parts of the day, like early morning or late afternoon.

Using dry flies that imitate the insects they're focused on can work well in these conditions. Making delicate casts and presenting your fly softly on the water's surface can entice them to strike.

Brown Trout Fly Fishing: Best Water Temps

Best Water Temperature: Nymphs

The best water temperature range for nymph fishing can vary depending on the season. In general, for nymph fishing:

- Spring: Look for water temperatures around 50 to 60 degrees Fahrenheit.
- Summer: Target temperatures between 55 to 65 degrees Fahrenheit.
- Fall: Aim for temperatures ranging from 45 to 55 degrees Fahrenheit.
- Winter: Seek out temperatures around 40 to 45 degrees Fahrenheit.

Best Water Temperature: Streamers

For streamer fishing to catch brown trout, the best water temperature range can vary with the seasons:

- Spring: Aim for water temperatures around 45 to 55 degrees Fahrenheit.
- Summer: Look for temperatures between 55 to 65 degrees Fahrenheit.
- Fall: Target temperatures ranging from 50 to 60 degrees Fahrenheit.
- Winter: Seek out temperatures around 40 to 50 degrees Fahrenheit.

Best Water Temperature: Dry Flies

For dry fly fishing to catch brown trout, the best water temperature range can vary with the seasons:

- Spring: Aim for water temperatures around 50 to 60 degrees Fahrenheit.
- Summer: Look for temperatures between 60 to 70 degrees Fahrenheit.
- Fall: Target temperatures ranging from 55 to 65 degrees Fahrenheit.
- Winter: Seek out temperatures around 45 to 55 degrees Fahrenheit.

Best Water Temperature: Mice Flies

For fishing with mice flies to catch brown trout, the best water temperature range can vary depending on the seasons:

- Spring: Look for water temperatures around 45 to 55 degrees Fahrenheit.
- Summer: Aim for temperatures between 55 to 65 degrees Fahrenheit.
- Fall: Target temperatures ranging from 50 to 60 degrees Fahrenheit.
- Winter: Seek out temperatures around 40 to 50 degrees Fahrenheit.

Is Water Temperature a Big Factor in Brown Trout Fishing?

Water temperature has a big impact on brown trout fishing and their behavior. Brown trout tend to be less active when the water is cold, like in winter or early spring. They might stay in deeper parts of the water where it’s warmer and feed less frequently.

Brown trout become more active as the water warms up in late spring and summer. They move to shallower areas, like riffles or runs, to find cooler and oxygen-rich water. Warmer water speeds up their metabolism, so they must eat more often.

In fall, brown trout become more active and aggressive in feeding as water temperatures cool down again. However, extremely cold water, like during winter, can make them less willing to bite.

Overall, the right water temperature can make brown trout more energetic and more likely to bite, while cold or warm water can slow down their activity.

Seasonal Water Temperature Guide for Brown Trout

Winter

In early winter, when water temperatures drop to around 40 to 45 degrees Fahrenheit (4.4 to 7.2 degrees Celsius), brown trout become less active and might move to deeper, slower-moving parts of rivers and streams. They focus on conserving energy rather than actively feeding. Fishing during the warmer parts of the day when the water temperature slightly rises can increase the chances of success. Using nymph flies that imitate aquatic insects close to the riverbed can work well during this time.

In the middle of winter, brown trout's metabolism slows down even more when water temperatures further drop to around 35 to 40 degrees Fahrenheit (1.7 to 4.4 degrees Celsius). They prefer deeper, quieter waters to minimize energy expenditure. Fishing very slowly with tiny nymphs or midge larvae imitations, presented right before them, can entice a bite.

In late winter, brown trout are the least active when water temperatures are at their coldest, around 32 to 37 degrees Fahrenheit (0 to 2.8 degrees Celsius). They often hold in the deepest pools where water temperatures are more stable. Fishing extremely patiently with small, dark-colored flies that resemble insects in their dormant state, such as midges or small stoneflies, can be effective.

Overall, in winter, fishing for brown trout can be tough due to their reduced activity. Warmer parts of the day and slow presentations with small, natural-looking flies are key strategies.

Spring

In early spring, brown trout wake up from their winter slowdown when water temperatures range from 40 to 50 degrees Fahrenheit (4.4 to 10 degrees Celsius). They become more active, moving from deeper areas to shallower spots like riffles and runs, where the water is more oxygen-rich. They focus on easy-to-catch food like insects and small fish. Using nymph flies that imitate underwater insects, and fishing them close to the riverbed, can work well during this time.

In the middle of spring, brown trout become even more active as water temperatures rise to around 50 to 55 degrees Fahrenheit (10 to 12.8 degrees Celsius). They feed on emerging insects and might be found near the surface. Dry flies that resemble insects on the water's surface can be effective, especially during hatches.

In late spring, brown trout are more active and more willing to chase their prey when water temperatures reach 55 to 60 degrees Fahrenheit (12.8 to 15.5 degrees Celsius). They can be found in various parts of the river, including pockets behind rocks or near fallen trees. Streamer flies that mimic small fish or large insects can be successful, as brown trout become more aggressive.

Brown trout fishing is good in spring when water temperatures are between 40 to 60 degrees Fahrenheit (4.4 to 15.5 degrees Celsius).

Summer

In early summer, when water temperatures rise to around 55 to 60 degrees Fahrenheit (12.8 to 15.5 degrees Celsius), brown trout become more active and move into faster currents like riffles and runs. They're hungry after the spawn and focus on insects like mayflies and caddisflies. Dry flies that imitate these insects on the water's surface can be successful during hatches.

In the middle of summer, brown trout feed actively as water temperatures increase to around 60 to 65 degrees Fahrenheit (15.5 to 18.3 degrees Celsius). They may move to deeper pockets with more shade to stay cooler during the day's heat. Nymph flies that mimic aquatic insects underwater can be effective, especially in the early morning or late evening.

In late summer, when water temperatures peak around 65 to 70 degrees Fahrenheit (18.3 to 21.1 degrees Celsius), brown trout's activity might slow down a bit due to warmer conditions. They may seek cooler, oxygen-rich areas like spring-fed creeks or shaded spots. Using streamer flies that mimic small fish and fishing during the cooler parts of the day can improve success.

Brown trout fishing can be good in summer when water temperatures range from 55 to 65 degrees Fahrenheit (12.8 to 18.3 degrees Celsius).

Fall

In early fall, brown trout become more active after the warm summer when water temperatures range from 50 to 55 degrees Fahrenheit (10 to 12.8 degrees Celsius). They move into shallower water and might be found near rocks, fallen leaves, or other structures. Brown trout start to feed more aggressively, focusing on insects and small fish. Using streamer flies that mimic small fish can be effective during this time.

In the middle of fall, brown trout continue their feeding spree as water temperatures drop to around 45 to 50 degrees Fahrenheit (7.2 to 10 degrees Celsius). They can be found in deeper pools or runs and might be more willing to chase larger prey. Using nymph or streamer flies resembling insects and small fish can work well, as brown trout become more aggressive.

In late fall, when water temperatures further decrease to around 40 to 45 degrees Fahrenheit (4.4 to 7.2 degrees Celsius), brown trout prepare for the upcoming winter. They focus on fattening up and might move to deeper, slower water. Nymph flies that imitate aquatic insects or smaller streamer patterns can still be effective, presented close to the riverbed.

Overall, in fall, brown trout fishing can be very good when water temperatures range from 45 to 55 degrees Fahrenheit (7.2 to 12.8 degrees Celsius). Brown trout are actively feeding, and using a mix of streamers and nymph flies can increase your chances of catching them.

Does Air Temperature Impact Brown Trout Fishing?

Air temperature affects brown trout fishing because it can influence the water temperature, affecting how brown trout behave. When the air is cold, like in winter or during chilly days, it cools down the water. Cooler water temperatures can make brown trout less active and move slower. They might become sluggish and less likely to bite.

Conversely, when the air is warm, like during spring and summer, it gradually warms up the water. Warmer water temperatures can make brown trout more active and willing to move around and feed. They become more energetic and might venture to shallower areas to find food.

In summary, air temperature is key in determining water temperature, directly impacting brown trout activity and feeding behavior.

How Cold is Too Cold for Brown Trout Fishing?

Brown trout fishing is usually less productive when the water temperature is very cold, below 40 degrees Fahrenheit (4.4 degrees Celsius). Brown trout might become slower and less active at this point, making them less likely to bite. If the air is also frigid, like during freezing winter days, it can further cool down the water, making the fishing conditions even more challenging.

In general, when both the air and water temperatures are extremely cold, it can indicate that brown trout are less likely to feed actively, and fishing might be tougher.

How Hot is Too Hot for Brown Trout Fishing?

For brown trout fishing, water temperatures that are too cold, below 40 degrees Fahrenheit (4.4 degrees Celsius), or too warm, above 70 degrees Fahrenheit (21.1 degrees Celsius), can make fishing less productive. When it's too cold, brown trout become less active and might not bite readily. Brown trout can become stressed when it's too warm because they prefer cooler water.

Similarly, if the air is too cold, like during frosty mornings or chilly days, it can impact the water temperature and slow down brown trout activity. If the air is too hot, like during scorching heatwaves, it can warm up the water and make brown trout less likely to bite.

In summary, brown trout fishing is usually best when the water temperature ranges from 50 to 60 degrees Fahrenheit (10 to 15.5 degrees Celsius) and when the air temperature is moderate and comfortable.

Storms & Weather Changes: Impact on Brown Trout Fishing

Storms and weather can affect brown trout fishing in different ways. Brown trout can become more active and feed more actively before a storm, like a rainstorm or a change in atmospheric pressure. This can create good fishing opportunities.

During a storm, however, fishing can become more challenging and even dangerous due to heavy rain, strong winds, and lightning. Brown trout might become less active and stop feeding during the storm's disturbance.

After a storm passes, the fishing can pick up again. Brown trout may continue feeding as water conditions stabilize. Rain can also wash insects and other food into the water, making brown trout more likely to bite.

In general, calm and mild weather is better for brown trout fishing, but sometimes the moments before and after a storm can offer great chances to catch them.

Click here to see the best water temperature for trout. Click here to see how to catch trout on cloudy days. Click here to see how to catch trout on sunny days. Click here to see how to catch trout on windy days. Click here to see the best water temperature for rainbow trout.

Eric Matechak

I am an avid angler and outdoorsman. I grew up fishing for anything that swims but really cut my teeth fishing for trout, chain pickerel, bass, and bullheads in my teenage years. Since then, I've lived across the country and have really taken that passion for fishing to a new level.

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PH PREFERENCE AND AVOIDANCE OF ADULT BROOK TROUT AND BROWN TROUT: INFLUENCE ON MOVEMENTS AND INTERACTIONS

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Abstract:
A recent analysis of Pennsylvania Fish and Boat Commission historical data collected from streams throughout Pennsylvania containing trout concluded that base-flow pH is strongly correlated to the observed segregation of Brook Trout (Salvelinus fontinalis) and Brown Trout (Salmo trutta). Populations of Brook Trout, which are native to Pennsylvania, predominated at pH<7.0 (mostly headwaters), while Brown Trout, an introduced species that has become naturalized in much of Pennsylvania, predominated at pH>7.0 (lower reaches). The decline of historic Brook Trout populations has been linked in part to competition with Brown Trout (Hudy 2005). The relationship between the segregation pattern observed and pH is significant because low pH may be acting as a barrier that prevents further invasion of Brown Trout into the headwaters, where Brook Trout populations remain strong. The overall goal of this study was to examine the influence of pH and species interactions on the distribution of Brook Trout and Brown Trout in Pennsylvania streams. The first study examined shifts in Brook Trout and Brown Trout pH preference/avoidance after exposure to different pH conditions. Adaptation to pH is important because the results of behavioral studies may differ depending on pH exposure history. Adaptation to pH is particularly important for Brook Trout and Brown Trout because these species are often segregated in streams with a pH gradient, suggesting that behavioral responses to pH differ between the two species. In order to study how the behavioral response differed between the two species, it was necessary to determine if pH exposure history altered behavioral response. Thus, hatchery-reared Brook Trout and Brown Trout were exposed to different holding pH treatments for seven days prior to determining their behavioral response to pH. Preference was determined in a long trough where a gradient of pH (4.0-7.0) was presented to fish. Steep gradient choice tanks were used to determine avoidance. iv I found that hatchery-reared Brook Trout and Brown Trout pH preference was not influenced by holding pH. Results of pH avoidance trials were similar to that of preference studies, in that holding pH did not alter pH avoidance of either species. This study suggested that individuals of these species can be held in the laboratory at a pH different from the source waterbody for a short period of time without altering preference or avoidance behavior. Thus, the pH of the laboratory source water was not adjusted for the purposes of examining preference and avoidance behavior of wild fish. The second study investigated the pH preference and avoidance of wild, adult Brook Trout and Brown Trout using the same methodology applied in the first study. The behavioral response of Brook Trout and Brown Trout to low pH is one of factor that may lead to the observed segregation pattern of the two species in Pennsylvania streams. The observed segregation pattern and behavioral responses to episodic events suggest that differences in the pH preferred or avoided may exist. Although pH preference and avoidance of juveniles have been established, the preference and avoidance of adults have not been examined. Wild, adult Brown Trout showed a preference for pH 4.0 while wild, adult

Brook Trout did not prefer any pH within the range tested (pH 4.0 – 7.0). Adult Brown Trout displayed a lack of avoidance at pH below 5.0, which is similar to that reported for juvenile Brown Trout. The avoidance pH of wild, adult Brook Trout (between pH 5.5 and 6.0) and Brown Trout (between pH 6.5 and 7.0) did not differ appreciably from earlier study results for the avoidance pH of juvenile Brook Trout and Brown Trout. A comparison of confidence intervals around these avoidance estimates indicates avoidance pH is similar among adult Brook Trout and Brown Trout in this study. However, the limited overlap of confidence intervals for avoidance pH values for the two species suggests that some Brown Trout will display avoidance at a higher pH v when Brook Trout will not. The results of this laboratory study indicate that adult Brook Trout – Brown Trout segregation patterns in Pennsylvania streams could be related to pH and that competition with Brown Trout could be mediating the occurrence of Brook Trout at some pH levels. The preference and avoidance pH results from this study were used to design field experiments involving species interactions and pH. The final study examined the effects of acidification and species interactions on the distribution of Brook Trout and Brown Trout. Although pH appeared to be correlated with the observed distribution patterns of Brook Trout and Brown Trout in Pennsylvania streams, our laboratory studies examining the avoidance pH of wild, adult Brook Trout and Brown Trout did not conclusively find that avoidance pH differs between these species. The lack of conclusive difference in the pH avoidance threshold did not rule out pH as a mediating factor. Interactions between Brook Trout and Brown Trout could lead to habitat partitioning in a stream. Brown Trout are considered superior competitors, but a physiological advantage may allow Brook Trout to dominate Brown Trout in headwaters, particularly if pH is lower. Thus, the behavior of wild, adult Brook Trout and Brown Trout (alone and in combination) was observed in study reaches that were manipulated to vary the level of acidity and CO_2. In the artificial stream channel, the majority of indwelling fish (fish that spent greater than 0 seconds on the treatment side during the control observation period) responded to acidification by moving to more neutral conditions (62% of Brook Trout and 68% of Brown Trout). Indwelling Brook Trout spent less time in acidic conditions during the acid treatment (41 ± 5%) than during the control period (94 ± 2%). However, elevated levels of CO_2 may have caused their avoidance at a higher pH. Indwelling Brown Trout spent less time in the acid conditions during the acid treatment (44 ± 4%) than during a control period (98 ± 1%). The proportion of vi time spent in the acid water by indwelling trout decreased as negative interactions with other fish (such as chasing) increased. Presence of the opposite species did not influence the proportion of time spent in the acidic conditions. The results of this study do not support the hypothesis that acidification mediates the segregation of Brook Trout and Brown Trout in Pennsylvania streams. Confounding factors, relating to changes in CO_2 associated with the acid manipulation, and issues relating to stocking density need further investigation to identify what role these may have played.

Brown Trout

The Brown Trout (*Salmo trutta*) is one of the trout species in Vermont that is not native. It was introduced to Vermont during the late 1800s, and now there are spawning populations in most of the drainage basins in the state.

They are commonly found in rivers and streams. Fish & Wildlife Department personnel carefully choose the lakes and ponds in which they stock Brown Trout, as the fish tend to grow quite large in these habitats and eat many smaller fish, including other stocked trout.

Habitat

The Brown Trout typically inhabits the lower reaches of cold-water streams, characterized by deep, slow-moving pools and runs. It also thrives in larger lakes of sufficient depth to maintain cool water temperatures year round. The Brown Trout is more tolerant of warm water temperatures and pollution than other species of trout.

As with other trout species, water temperature is a major limiting factor for Brown Trout. Optimum temperatures range from 53°F to 66°F, although they can tolerate temperatures near 80°F for short periods of time. Brown Trout tolerate pH levels from 5.0 to 9.5 but the optimal range is between 6.8 and 7.8.

Optimal brown trout habitat in streams is characterized by:

- 50% to 70% pools and 30% to 50% riffle runs;
- A rocky bottom in riffle-run areas with no silt;
- A gentle-sloping stream with slow, deep pools;
- Relatively constant stream flows;

- Overhead cover where streams are wide and deep.

Reproduction

Brown Trout usually live for five to six years, although ages of eight and nine years are not uncommon in waters that are not frequently fished. They generally grow at faster rates and achieve larger sizes than Brook Trout or Rainbow Trout.

In Vermont streams, Brown Trout tend to reach 5-9 inches after two years, 8-11 inches by their third

old Brown Trout reaching 11-18 inches and four-year-olds averaging 13-21 inches in length. Relatively few Brown Trout older than four years have been collected in fishery surveys, but every year anglers catch some very large fish.

In Vermont streams, the male Brown Trout matures at two to three years of age and the female matures one year later. Some lake-dwelling strains may not mature until the fourth or fifth year.

Spawning typically occurs from late October through December, when water temperatures reach an optimum range of 44°F to 48°F. Lake populations must have access to suitable tributary streams to reproduce. They sometimes migrate considerable distances to reach tributaries or headwaters with well-oxygenated gravel at the tail of pools.

Although Brook Trout will exclusively select groundwater upwellings for spawning sites, these areas may or may not be used by Brown Trout. The female digs a well-defined redd or shallow hole, which takes several days. When she is finished, one or more males will join her to complete the fertilization of her eggs.

Optimal incubation temperatures range between 36°F to 55°F, but tolerable levels range from 32°F to 59°F. Like Brook Trout, Brown Trout eggs overwinter in the gravel. Incubation times vary from 148 days at 35°F (typical of Vermont streams) to 30 days at 57°F.

Young fish, called fry, emerge from the gravel after absorbing their yolk sacs. They disperse quickly, immediately establishing territories in shallow, low-velocity pools with rocky surfaces. This habitat is also preferred by larger juvenile Brown Trout, which may force the fry to the edges of pools and riffles on smoother surfaces.

Diet

Brown trout are opportunistic feeders, but are perhaps more selective than other trout species. Aquatic and terrestrial insects make up the primary food source of brown trout that are less than ten inches in length. As they become larger, they shift more to fish and crustaceans. Mature brown trout in streams feed primarily at night, while those in lakes are more likely to feed during daylight hours.

Management

In Vermont, over 180 lakes and ponds and 3,800 miles of streams and rivers are managed by the Vermont Fish & Wildlife Department for one or more trout species. The department must decide whether or not to stock an area, where to set length and creel limits and gear restrictions, and when and where to allow or not allow fishing by anglers.

The general areas the state considers in management are:

- Habitat capacity, or quality and quantity of existing fish habitat in the water;
- Fishing pressure, or how heavily people fish the area;
- The productivity or food base of the stream, river or lake;
- The present species of fish that are managed in the body of water;
- Whether natural reproduction of the trout species would be supported;
- Timing and duration of spawning runs;
- Public input.

Steps the Vermont Fish & Wildlife Department make in managing trout in Vermont start with monitoring and evaluating the existing trout population. Biologists take care to protect the selected habitat of the trout and partner with others to implement restoration efforts according to their evaluations. After evaluating the stream, river or lake, they stock trout if needed.

Stocking is determined with one of their three techniques: "put-grow-take," "put-take," or "species recovery" (specific for Atlantic salmon).

- Put-take: Catchable-size trout (greater than 6" and often 8-10" long) are stocked in areas where fishing pressure is high, but habitat does not support sufficient natural reproduction or growth of young fish to meet fishing demands. Put-take stocks are removed by fishing usually within one season. The fish that are not caught, rarely survive to the following season. This method of stocking is used primarily in rivers and streams.
- Put-grow-take: Smaller-sized fish stocked in spring to "grow" to catchable size before being caught. Often used in ponds and lakes where fish can survive the winter and where adequate food is available for fish survival. This technique is usually used to maintain populations where spawning habitat is lacking.
- Species Recovery: Stocking of fingerlings with the goal of reestablishing the trout species in a particular body of water.

Learn more about trout management

Status

The brown trout was introduced to Vermont during the late 1800s and the species soon established a firm foothold in all the major drainage basins. It frequents many of the streams and rivers also occupied by brook trout and rainbow trout.

Brown trout have a preference for the deeper, slower and more fertile downstream river areas. Natural spawning populations are common to most drainage basins in the state, nevertheless, many of these waters are also stocked with catchable-sized brown trout to supplement the wild resource and improve fishing opportunities.

The establishment of wild brown trout populations in a large number of waters has often been at the expense of the native brook trout. For example, the Batten Kill in the southwestern region of the state was historically a brook trout stream, but the brown trout, introduced around 1926, have largely replaced the native species.

On the other hand, the establishment of brown trout populations has given anglers another type of trout to catch in Vermont. The brown trout is also well adapted to many lowland river areas, to which brook trout are not well suited. Brown trout often grow to trophy sizes in these waters.

Brown Trout populations in lakes and ponds are relatively limited in Vermont. Even though Brown Trout adapt well to certain pond and lake habitats, Vermont Fish & Wildlife Department has decided to only stock rivers and streams.

Brown Trout have a tendency to accumulate in abundance in lakes and ponds because they out compete other trout species and withstand fishing so well. They also tend to grow larger than other trout species and then feed heavily on other fish, including recently stocked smaller trout. Brook and Rainbow Trout do not pose such problems when they are stocked in lakes and ponds.

- American Eel
- Bowfin
- Brook Trout
- **Brown Trout**
- Lake Trout
- Land-locked Salmon
- Longnose Gar
- Northern Pike
- Rainbow Trout
- Rock Bass
- Slimy Sculpin
- Smallmouth Bass
- White Perch
- White Sucker
- Yellow Perch
- Mammals
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Angler's Guide to Walleye Fishing in Georgia

Georgia Department of Natural Resources, Wildlife Resources Division
Fisheries Management Section
February 2018

Walleye in Georgia

Walleye is the most popular sport fish in the northern states and Canada, but it remains a relatively obscure species to most Georgia anglers. With expanding populations and an excellent reputation as table fare, walleyes are gaining the attention of increasing numbers of Georgia anglers. Walleye is a coolwater fish that is native to the Tennessee River and Coosa River Valley systems that flow through the heart of Fannin, Union, and Towns counties in northeast Georgia and in Dade, Walker and Catoosa counties in northwest Georgia. Rivers with Native American names like the Coosawattee, Conasauga, Etowah, Oostanaula, Toccoa, Nottely, and Hiwasee once contained native walleye populations.

Native walleye declined in the state many years ago for a variety of reasons including loss of spawning habitat and overfishing. To rebuild and expand their distribution across North Georgia, a walleye stocking program was initiated in the 1960s. These early stockings were largely unsuccessful in all but a few mountain lakes; therefore, the walleye stocking program ceased in 1968.

During the 1990s, declining numbers of walleye coupled with the rapid expansion of illegally introduced blueback herring sparked a renewed interest in re-establishing the walleye stocking program. In 2002, a fledgling walleye stocking program was reborn in Georgia. Today, eleven lakes receive annual stockings of walleye. These include lakes Seed, Rabun, Tugalo, Yonah and Hartwell in the Savannah River drainage, lakes Chatuge and Blue Ridge in the Tennessee Valley plus Lake Lanier, Carters Lake, and two lakes in the Rocky Mountain Public Fishing Area.

This guide was written to provide anglers with seasonal information on where, when and how to catch walleye in Georgia. GADNR staff is also available to answer more specific questions. Contact information for walleye lakes in Georgia is provided in the table below.

Reservoir	GADNR Phone Number
Lakes Burton, Seed, Rabun, Tugalo, Yonah, Hartwell, Chatuge and Lanier	706/947-1507, 706/947-1502 770/535-5498
Blue Ridge Lake, Carters Lake, and Rocky Mountain Public Fishing Area	706/295-6102

Late-Winter / Early-Spring Fishing Tips

By late-winter, the natural instincts of adult walleyes draw the population to the spawning grounds for the annual ritual of laying and fertilizing eggs. Identifying potential spawning areas is critical to angling success from February to April. For most lakes in Georgia, the major walleye spawning areas are in the headwaters in very shallow water with rocky bottoms, like the picture below of a major spawning area in the headwaters of Lake Rabun. Pre-spawn walleye stage in deeper water near the spawning grounds for several weeks while they wait for the water to reach the critical temperature of 48°F to 50°F. No fancy gear or tackle are needed to catch these fish. Simply drifting nightcrawlers slowly along the bottom through these staging areas is the best way to catch pre-spawn walleye. Walleye are finicky feeders and may prefer small jigs tipped with minnows or a curly tailed grub or even a crankbait, such as a sinking Rapala or Shad Rap. Maintain a slow but steady retrieve as you work these lures across the river bottom. Be patient and stay focused for a light tap or steady tug on the line.

Male walleyes will be the first to reach the spawning grounds in late-February, and they will remain in the area through mid-April. At night, male walleyes will swim into very shallow water with rocky bottoms in hopes of finding a female ready to spawn. During the day, they will retreat to the shelter of nearby deeper water to avoid the bright sunshine. Female walleyes behave much differently than their male counterparts. Females will only move in and out of the spawning grounds for brief periods at night to broadcast their eggs onto the rocky bottoms where they will be fertilized by several males. When her heavy egg sac is emptied, she will leave the spawning grounds for the season. Because of the differences in spawning behavior between male and female walleyes, anglers can expect the bulk of their catch to be males that range in size from 2 to 4 lb. GADNR has been stocking walleye into north Georgia lakes since 2001. This is sufficient time to allow many females to reach trophy size. In fact, GADNR biologists have collected walleye over 12 pounds during the spawning season on some lakes. The state record was caught in February 2016 and weighed 14 lb 2 oz.

From March through early-April, walleyes are easiest to catch in the evening hours when they venture into the shallows of the spawning grounds. In fact, some anglers talk about the "golden hour" right before nightfall as the time when walleyes bite best. Shallow water walleyes are most easily caught using a 3/8 oz jig tipped with a live minnow, nightcrawler, or plastic grub. Shallow running minnow imitations are also effective during the nightly spawning run. Whatever your preference of baits or lures, the presentation is similar. Cast across the rocky structure and make a slow but steady retrieve. The bite is rarely aggressive but feels more like sudden resistance. A slight upward swing of the rod is all that is needed to set the hook. Walleyes in shallow water are easily spooked, so finesse and stealth are critical, even at night. The rocky, shoal areas below the dams at lakes Burton, Seed, Tugalo, and Yonah offer easy bank access for nighttime anglers. Boats are required to reach spawning fish on lakes Tugalo, Hartwell, Lanier, Carters, and Blue Ridge. Use caution when fishing below dams because water levels may rise suddenly. Check water release schedules before your trip.

Late-Spring / Summer Fishing Tips

After the spawning season, walleye return to the main lake to resume their daily ritual of finding food and searching for sheltered resting areas. Because walleye prefer cool water temperatures (65 to 72ºF), small schools of walleye will congregate together in deeper water during the summer months where temperatures are more suitable. Walleye orient to structure, especially bottom structure, in their preferred depth zone, only leaving these hiding spots for opportune moments to feed on herring, shad, yellow perch, sunfish, and crayfish. The key to successful walleye fishing in the summer is to determine areas of the lake where walleyes are most likely to congregate. In the mountain lakes, likely congregation areas occur on points and the mouth of coves at target depths that range from 15 to 25-feet in early summer and progressively increase to 30 to 50-feet by summer's end. During the summer, most walleye can be found on the lower half the lake.

The best presentation for walleye in the late-spring and summer months is a simple nightcrawler that is worked slowly along the bottom near structure. Slow trolling can also be effective under low-light and nighttime conditions using a weighted bottom bouncer armed with an in-line spinner and tipped with a nightcrawler or lively blueback herring or even deep diving crankbaits in perch, fire tiger and shad color patterns. Long points, humps, and weed beds on the lower end of the lake are the best places to search for summertime walleyes. Structure fishing with finesse and diligence will ultimately be the keys to hooking into some walleyes during the warmer months.

Several reservoirs in north Georgia are summer standouts because of their relatively small size and ease of locating deepwater fish. Lakes with excellent summer walleye fishing include Lake Yonah, Lake Tugalo, and Lake Rabun. The search for summer walleye should begin on the lower one-third of the reservoir in the mouth of coves, on long points, or around any deepwater structure. There is one unusual twist to the traditional summertime, deepwater pattern on these lakes. After heavy rain events, walleyes will frequently move into the shallow headwaters to feed in the fast-flowing, turbid waters. These opportunities are unpredictable but worth taking advantage of when they occur because the walleyes that move into the shallows are generally big and hungry!

Fall Fishing Tips

When the tree leaves turn colors during the cool days of October, walleyes emerge from their deepwater refuge to search the shallows for unsuspecting prey. During the fall, walleye actively feed during low light conditions and throughout the night. The moon phase can also influence walleye fishing success, with the best night time fishing occurring under a full moon. Once again, search the points and adjacent flats on the lower one-third of the reservoir at dawn, dusk or at night for shallow water feeding activity.

Cool weather walleye feed on a wide variety of prey items, including blueback herring, shad, yellow perch, bluegill, minnows, and crayfish. During the fall months, walleye will typically bunch up around downed trees and other structures in 20 to 40-feet of water, especially in the outer bends of the river channel. Anglers should nibble around the edges of these structures with a small jig that is tipped with a minnow or nightcrawler. Trolling with live herring or deep-diving crankbaits is a secondary option at this time of year.

Winter Fishing Tips

From December through February, water temperatures on most north Georgia lakes dip into the mid to low 40s. Cold winter temperatures reduce a fish's desire to feed. For those brave enough to endure the cold, live baits presented around bottom structure at depths from 30 to 60-feet, especially near the dam, can produce a few strikes. Although winter walleye may be bunched up, they are largely inactive. Patiently dangling a live herring or medium shiner or even a jigging spoon in front of their nose may be sufficient temptation to draw a strike. If one fish is caught or located, you can be sure that others are nearby. The key to successful winter fishing is to work your baits slowly around every nook and cranny of bottom structures.

In late winter, warm rains can concentrate walleye in tributary areas of the lake. Tributary runoff is often a few degrees warmer than the main lake and sometimes more turbid in color. These conditions are favorable to the baitfish that walleye prey upon. Follow the warming water to the bait and you will find the predators, including walleye.

Wes Carlton with his state record walleye from Lake Rabun that weighed 14 lb 2 oz.

Walleye Fishing Seasonal Calendar at a Glance

Color-Coded Seasonal Index 🟢 = Good 🟡 = Fair 🔴 = Low

RESERVOIR	FEB – APRIL	MAY – SEPT	OCT – JAN
Seed	🟢	🟡	🟡
Rabun	🟢	🟡	🟢
Tugalo	🟢	🟢	🟢
Yonah	🟢	🟢	🟢
Hartwell	🟢	🔴	🟡
Lanier	🟡	🔴	🔴
Blue Ridge	🟡	🟡	🟡
Carters	🟡	🟡	🟢
Rocky Mountain Public Fishing Area	🟡	🟡	🔴

Seasonal Tips, Tactics & Locations by Reservoir

Color-Coded Seasonal Index = Good = Fair = Low

RESERVOIR	FEB – APRIL	MAY – SEPT	OCT – JAN
Seed	Target the headwaters. Fish from Burton Dam downstream to the mouth of Sawmill Creek.	Fishing is best on the bottom near the dam, especially in late summer. Target downed trees.	Target bottom structure on the outside bends of the river channel.
Rabun	Target the headwaters. Fish on shore from the Low Gap Bridge upstream to Seed Dam at night. During the day, fish downstream of the bridge with nightcrawlers, jigs or perch-colored crankbaits.	Target main lake points and bottom structure in 20-30 feet of water on the lower end of the lake. Live herring, nightcrawlers and shiners work best. At night, cast to shallow points with small crankbaits.	Target bottom structure on the outer bends of the river channel on the lower half of the lake. At night, walleye move into shallow water on points and adjacent flats to feed on small sunfish and perch.

RESERVOIR	FEB – APRIL	MAY – SEPT	OCT – JAN
Tugalo	Target the headwaters. Go upstream as far as possible by boat on both river arms to fish. Fish on the bottom with jigs or nightcrawlers.	Slowly drag nightcrawlers or jigs tipped with a shiner along deepwater points and brush piles in 40-60 ft of water.	Fish around downed trees out to the edge of the river channel at depths from 30-50 ft. At night, fish the points with small crankbaits or jigs.
Yonah	Target the headwaters at the base of Tugalo Dam and downstream to the first bend. Drift nightcrawlers across the rocky bottom or slowly troll crankbaits along the rocky banks near the campground.	Target bottom structure along the bends in the river channel. Drift nightcrawlers on the bottom or use vertical jigs in 45 ft of water from the Big Rock face at mid-lake downstream to the dam.	Walleye will be concentrated around bottom structure in 20-40-feet of water, especially on the edge of the river channel and in the deep bends of the channel. Use nightcrawlers, minnows or vertical jigs.
Hartwell	Target the headwaters from the Walker Creek boat ramp all the way to Yonah Dam. Fish with shallow-running crankbaits & floating lures.	Because of Hartwell's large size, it is difficult to target walleye in the summer months.	Target standing timber in 30-feet of water on main lake points in the Eastanollee Creek area. A live shiner is the best bait choice.

RESERVOIR	FEB – APRIL	MAY – SEPT	OCT – JAN
Lanier	Target the headwaters from upstream from Belton Bridge on the Chattahoochee River around the Highway 400 Bridge on the Chestatee River. Use crankbaits, Rapalas, or nightcrawlers.	Target brush piles in 30-50 feet of water on the lower half of the lake. Live herring or jigs tipped with a minnow are the best bait choices.	Target brush piles on the lower half of the lake. Also consider vertical jigging with spoons near the edge of the river channel in the mid and upper-lake.
Blue Ridge	Target the shoal area in the headwaters. Use shallow running crankbaits, floating lures or jigs.	Target main lake points and deepwater humps near the river channel on the lower end of the lake. Vertical jigs and flex-it spoons are best bets at a depth around 50-ft.	Target main lake points on the lower end of the lake. Use shallow running crankbaits or jigs fished near the shore during low light conditions.
Carters	Target the headwaters area from Ridgeway Boat Ramp upstream to the shoals in the Coosawattee River.	Gradual main lake points and submerged timber offer good fishing in May and June.	Fishing is best between Ridgeway Boat Ramp down to about the middle of the lake.

RESERVOIR	FEB – APRIL	MAY – SEPT	OCT – JAN
Rocky Mountain Public Fishing Area Antioch Lake Heath Lake	Early spring walleye will congregate on shallow rocky bottoms.	Walleye will concentrate near the bottom in deep water on points and structure.	Fish summer habitat areas. Under low light conditions, fish the shallows.

For More Information

We hope the tips provided in this fishing guide were helpful and will improve your chances of catching walleye in Georgia. Now that you know where, when, and how to fish for walleye in Georgia, we hope that you will be able to fill your stringer and the dinner plate. For more information about fishing in Georgia, we invite you to visit our website at **www.gofishgeorgia.com**. Volumes of information are also available on the internet. Here are two favorites:

www.walleyefishingsecrets.com
www.in-fisherman.com/walleye

Good luck and good fishing!

The Wildlife Resources Division is working to benefit the fisheries resources and anglers of Georgia!

esa ECOSPHERE

Water clarity and temperature effects on walleye safe harvest: an empirical test of the safe operating space concept

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Abstract. Successful management of natural resources requires local action that adapts to larger-scale environmental changes in order to maintain populations within the safe operating space (SOS) of acceptable conditions. Here, we identify the boundaries of the SOS for a managed freshwater fishery in the first empirical test of the SOS concept applied to management of harvested resources. Walleye (*Sander vitreus*) are popular sport fish with declining populations in many North American lakes, and understanding the causes of and responding to these changes is a high priority for fisheries management. We evaluated the role of changing water clarity and temperature in the decline of a high-profile walleye population in Mille Lacs, Minnesota, USA, and estimated safe harvest under changing conditions from 1987 to 2017. Thermal–optical habitat area (TOHA)—the proportion of lake area in which the optimal thermal and optical conditions for walleye overlap—was estimated using a thermodynamic simulation model of daily water temperatures and light conditions. We then used a SOS model to analyze how walleye carrying capacity and safe harvest relate to walleye thermal–optical habitat. Thermal–optical habitat area varied annually and declined over time due to increased water clarity, and maximum safe harvest estimated by the SOS model varied by nearly an order of magnitude. Maximum safe harvest levels of walleye declined with declining TOHA. Walleye harvest exceeded safe harvest estimated by the SOS model in 16 out of the 30 yr of our dataset, and walleye abundance declined following 14 of those years, suggesting that walleye harvest should be managed to accommodate changing habitat conditions. By quantifying harvest trade-offs associated with loss of walleye habitat, this study provides a framework for managing walleye in the context of ecosystem change.

Key words: adaptation; climate change; ecosystem change; fisheries; harvest; lake; Mille Lacs; oligotrophication; safe operating space; thermal–optical habitat; walleye; water clarity.

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Introduction

Freshwater resources are threatened by environmental change, including climate change, land-use change, invasive species, and harvest (Carpenter et al. 2011). Ecosystem responses to these drivers of global change may be non-linear, responding gradually until a tipping point or threshold is reached from which recovery can be difficult or impossible (Scheffer et al. 2015, Carpenter et al.

2017). The safe operating space (SOS) concept for managing ecosystems identifies the boundaries of acceptable conditions that are defined by interactions between continental or global scale drivers and local management (Scheffer et al. 2015). Theory suggests that by following the boundaries of the SOS, local management actions can be adjusted in response to environmental change to maintain ecosystem services and increase resilience. However, empirical tests of this important resilience concept on scales relevant to natural resource decision-making are lacking (Carpenter et al. 2017). Here, we present an empirical test of the SOS concept based on walleye (*Sander vitreus*), an economically and ecologically important freshwater fish species. We estimate the effect of changing habitat on sustainable harvest of walleye, identify the boundaries of the SOS for walleye harvest as a function of habitat, and show that safe harvest levels based on the SOS differ from those based solely on traditional fisheries models.

Walleye prefer low water clarity (Ryder 1977) and cool temperatures (Christie and Regier 1988). Walleye are low-light specialists due to a specialized retinal structure known as the *tapetum lucidum* that develops during the first year of life and allows them to successfully forage in dim conditions (Ali and Anctil 1977, Vandenbyllaardt et al. 1991). For most lakes, Secchi depths of 2–3 m are optimal for walleye (Lester et al. 2004), and increasing clarity above this range reduces optical habitat area. Thermal habitat area can be positively affected by water temperature due to increased growing season duration (Fig. 1), or negatively affected if temperatures exceed upper thermal limits. A lake's clarity, temperature, and bathymetry determine its thermal–optical habitat area (TOHA), that is, the area of a lake in which optical and thermal conditions for walleye overlap. A lake's TOHA is positively related to walleye production and catch rates at broad spatial scales (Lester et al. 2004, Tunney et al. 2018). Increasing water clarity and warming temperatures are associated with declining walleye and increasing Centrarchid (sunfishes and black bass) populations in lakes throughout North America (Robillard and Fox 2006, Hansen et al. 2015, Irwin et al. 2016). It is assumed that temporal trends in TOHA will influence walleye carrying capacity and yield (Lester et al. 2004), but to date, empirical tests of the effects of changing thermal–optical habitat on walleye populations are lacking (but see Chu et al. 2004).

Most fisheries models and stock assessments assume that relationships between stock size and population rates are stationary, and set harvest policies accordingly (Walters 1987). However, climate change, invasive species, harvest, and other stressors can alter productivity, with important implications for sustainable harvest policies (Walters et al. 2008). Sustainable fisheries management in the 21st century must account for the effects of global change (Paukert et al. 2016), although few concrete examples exist of recreational fisheries management systems that explicitly incorporate environmental change. The SOS of a recreational fishery is defined by environmental conditions and local management, and harvest reductions may compensate for habitat loss and prevent population collapse as conditions change (Fig. 1; Carpenter et al. 2017). Under this framework, long-term harvest is increased by adapting annual harvest in response to changing environmental conditions (Fig. 1).

In this study, we quantify relationships between water clarity and temperature, walleye habitat, and safe harvest. Our study focuses on Mille Lacs, Minnesota, USA, where walleye populations have dramatically declined since the 1990s. Due to the lake's popularity and economic importance, strong social and political pressures exist to restore walleye in Mille Lacs to support previous levels of harvest. However, if ecological changes have altered the productive capacity of the lake, harvest may need to remain low to maintain a sustainable fishery. The objectives of this study were to (1) quantify changes in walleye habitat area due to changing water clarity and temperature, and (2) quantify the effects of habitat area and predators on sustainable walleye harvest levels in an empirical test of the SOS concept.

Methods

Study area

Mille Lacs is a large (519 km^2), shallow (mean depth = 8.7 m), mesotrophic, polymictic lake located in central Minnesota, USA (46.233, −93.6502). Mille Lacs was historically one of Minnesota's most popular and productive walleye fisheries, but the walleye population and thus harvest has declined since the 1990s (Fig. 2;

Venturelli et al. 2014). The timing of this decline coincides with many changes, including warming temperatures (Fig. 2), changes in the fish community such as increasing smallmouth bass (*Micropterus dolomieu*) and fluctuating northern pike (*Esox lucius*) abundance (as measured by gillnet catches in standardized surveys; Fig. 2), the establishment of an Ojibwe tribal fishery in 1997 when treaty rights were reaffirmed (Minnesota v. Mille Lacs Band of Chippewa Indians 1999), and the invasion of zebra mussels in 2005 and spiny water flea in 2009 (MN DNR 2018). Notably, a marked increase in water clarity co-occurred with the onset of walleye declines, with Secchi depth changing from an average of 2.5 m from 1977 to 1996 to 3.5 m from 1997 to 2016 (Fig. 2). Other water quality data are sparse, but suggest that total phosphorus concentrations were higher in the 1970s through early 1990s than during the 2000s (Fig. 2; Heiskary and Egge 2016).

Walleye data

Walleye population size in Mille Lacs is estimated annually using a statistical catch at age (SCAA) model (Schmalz and Treml 2014). The SCAA model projects population numbers by sex, age, and length using fishery-dependent and fishery-independent data. Fishery-independent data include sex- and age-specific gillnet catch rates, catch rates of age-0 and age-1 walleye from fall electrofishing, and six independent mark–recapture population estimates. Outputs from the SCAA model were used as observations in the SOS model (described below). Relevant outputs used here include annual population estimates of age-3 and older walleye and total walleye kill from 1987 to 2017 (Fig. 2). Total kill includes walleye harvested by tribal fisheries, walleye harvested by recreational anglers (estimated from non-uniform probability access-based creel surveys; Pollock et al. 1994), and walleye killed via hooking mortality in the recreational fishery (estimated from creel surveys and a temperature-dependent statistical model; Reeves and Bruesewitz 2007). For brevity, these three sources of walleye mortality are collectively referred to as harvest throughout. The SCAA safe harvest limit was set at 24% of the biomass of walleye ≥35.6 cm (14 in) in total length from 1997 to 2014 (Minnesota v. Mille Lacs Band of Chippewa Indians 1999). Actual harvest quotas were negotiated based on these SCAA limits as well as additional information, and total walleye kill was always lower than SCAA safe harvest limits during this period (M. Treml, *unpublished data*). Declining populations have led to increasingly strict walleye harvest regulations in the late 2000s (Schmalz et al. 2011), and recreational harvest has been closed at various times from 2015 to 2017.

Optical, thermal, and thermal–optical habitat area

To estimate changes in walleye habitat area, we quantified optical, thermal, and TOHA for Mille Lacs for each day of 1980–2016. We used a combination of observed data, hydrodynamic modeling, and statistical modeling to reconstruct thermal–optical parameters. Water clarity was measured by Secchi depth (Appendix S1: Table S1) and converted to daily light extinction coefficients using a non-linear hierarchical model (Appendix S1). Daily water temperature profiles were estimated using an open-source hydrodynamic model (General Lake Model v2.2; Hipsey et al. 2019), modified to incorporate daily estimates of light attenuation. The temperature model was calibrated to in situ temperature data using a Nelder-Mead gradient descent algorithm, whereby the overall root-mean-squared error (RMSE) was minimized by altering model parameters (Appendix S1: Table S2; final RMSE of 1.26°C).

Daily water temperature and clarity estimates were combined to calculate daily TOHA following Lester et al. (2004), with minor modifications as described in Appendix S1 (for R code, see Winslow et al. 2017). Thermal habitat area was defined by temperatures for which simulated walleye growth rates were within 50% of the maximum from bioenergetics model simulations (11–25°C; Lester et al. 2004). We calculated thermal habitat area as lake benthic area for which water temperature fell within this range. Mille Lacs does not stratify, so habitat area calculations included the entire lake bottom. Optical habitat area was defined as lake benthic area for which estimated light levels fell between 8 and 68 lux (Ryder 1977, Lester et al. 2004). Thermal habitat area, optical habitat area, and the combination (TOHA) were expressed as the total benthic area satisfying the aforementioned criteria for each day. Daily estimates were summed to calculate annual habitat area estimates. This total annual area estimate was divided by the total

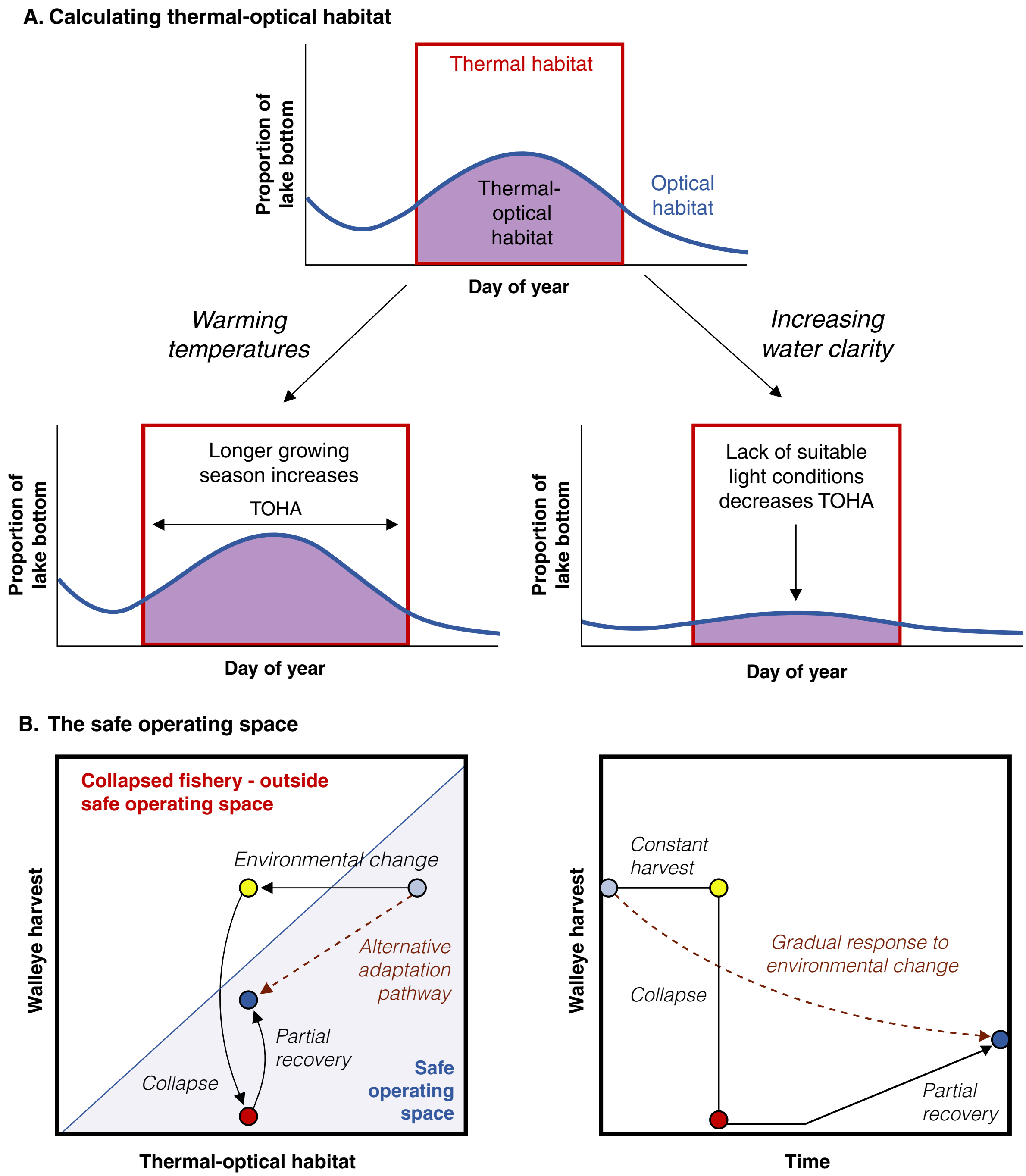

Fig. 1. (A) Thermal–optical habitat was calculated for each day as the proportion of lake bottom area with both optimal thermal and optical conditions and summed across all days of each year. In an unstratified lake that does not usually exceed upper thermal limits for walleye such as Mille Lacs, the entire lake bottom is thermally optimal for each day that temperatures fall within the optimal range, and warming temperatures increase this duration (but can also cause water temperatures to exceed thermal limits for optimal growth on some days). Optical habitat changes daily and seasonally as a result of diurnal and seasonal sun angle and seasonality of water clarity. In Mille Lacs, increasing water clarity reduces optical habitat as conditions become too bright throughout the

(Fig. 1. *Continued)*

water column for most hours of most days. (B) The safe operating space (SOS) is defined by both habitat and harvest. Environmental change such as increasing water clarity and reducing habitat can push the system out of the SOS (yellow dot), meaning that previously sustainable harvest levels now exceed safe harvest limits and the population collapses (red dot). Harvest reductions can move the system back to the SOS, and harvest will gradually increase to a new equilibrium (dark blue dot). If harvest is gradually decreased as conditions change (dashed orange line), total harvest over the time interval (area under the dashed orange curve) will be much larger than if the population is allowed to collapse (area under the black line). Even though the final rate of annual harvest is the same in the final year, the total harvest across all years is greater in the case where harvest adapts to changing habitat.

benthic area times the number of days in the year. Thus, habitat area is expressed as the proportion of the maximum potential habitat area averaged across the entire year (Fig. 1A). Three-year moving averages of annual TOHA were used as inputs to the walleye population model.

Walleye population model and the safe operating space

We assessed the effects of habitat area on walleye abundance and harvest using a previously studied model of fish population dynamics (Carpenter 2002). This model allows for a SOS (Carpenter et al. 2017) that is influenced by harvest and lake conditions. The general form of the population models we considered was

$$x_{t+1} = x_t \exp[f(x_t, H_t, P_t, b_i)] \exp(e_t) - F_t \tag{1}$$

here $f(\ldots)$ is a particular model form (Eqs. 2a, b), x_t is the number of age-3 and older walleye in year t, H_t is the TOHA (averaged across years $t-2$, $t-1$, and t), P_t is the catch per net night of northern pike and smallmouth bass from gillnet surveys, b_i are fitted parameters, F_t is the number of walleye killed by harvest (including hooking mortality), and e_t is the model residual error assumed to be normally distributed, mean 0, variance σ^2 estimated from the data, and uncorrelated over time. Both x_t and F_t were estimated by the SCAA model using observations from Mille Lacs (Schmalz and Treml 2014). Models were fit by maximum likelihood and compared using AIC (Akaike 1973).

Two model forms fit the data relatively well:

$$f(x) = b_1 x_t - b_2 \frac{x_t^2}{H_t} - b_3 P_t x_t \tag{2a}$$

$$f(x) = b_1 x_t - b_2 \frac{x_t^2}{H_t} \tag{2b}$$

Both models include a linear autoregressive term (b_1) and a quadratic habitat term (b_2) analogous to a logistic equation. Model (2a) includes a predator term (b_3) with a linear (i.e., Lotka-Volterra) functional response. We considered more complicated functional responses (Walters and Martell 2004) and none fit as well as a linear response. In (2a) and (2b), we write $f(x)$ instead of $f(x_t, H_t, P_t, b_t)$ to simplify notation.

The SOS boundary is the highest possible fishing mortality that still has a positive equilibrium growth rate for given and fixed values of H and P (Carpenter et al. 2017). Solutions to Eq. 3 with $e_t = 0$ provide deterministic equilibrium walleye population sizes.

$$0 = x\left[\exp(f(x)) - 1\right] - F \tag{3}$$

The edge of the SOS occurs where the flat line F is tangent to the hump-shaped relationship between population size and population growth rate as described by Eq. 3. F_s is the maximum walleye mortality, and x_s is the corresponding walleye population for specific fixed levels of habitat area and predator biomass. If particular values x_s and F_s are at the edge of the SOS, then (3) is satisfied and the first derivative of (3) is zero. Thus, x_s can be found by solving the first derivative of (3) with respect to x, which is

$$0 = \frac{\mathrm{d}}{\mathrm{d}x}\left\{x\left[\exp(f(x)) - 1\right] - F\right\}$$

$$0 = x\left[\frac{\mathrm{d}}{\mathrm{d}x}f(x)\right]\exp(f(x)) + \left[\exp(f(x)) - 1\right] \tag{4}$$

Given estimates of the parameters b_i, (4) is solved numerically for x_s using the uniroot() package in R (R Core Team 2017). Then, F_s can be found by solving (3) using x_s:

$$F_s = x_s\left[\exp(f(x_s)) - 1\right] \tag{5}$$

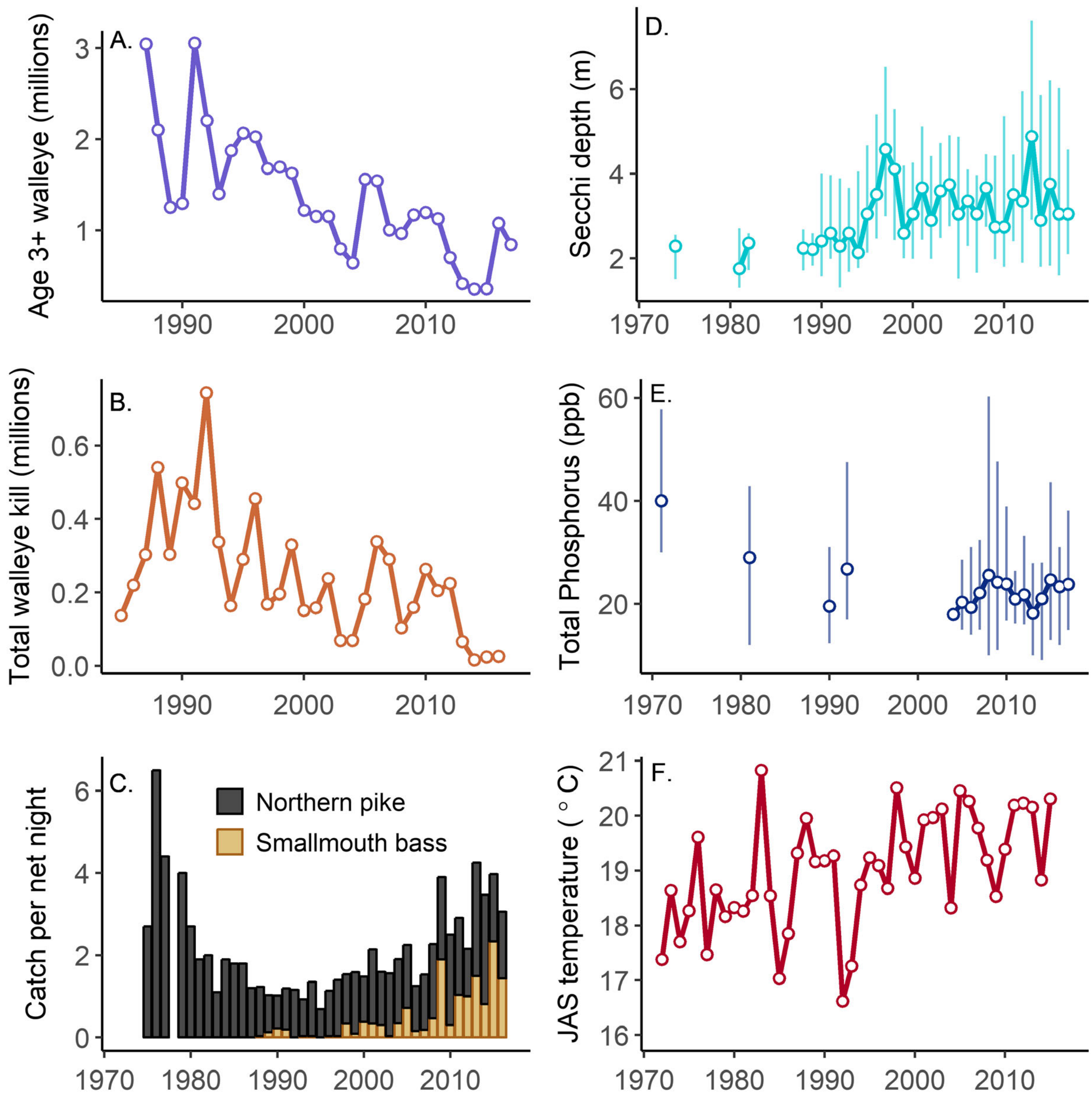

Fig. 2. Annual time series of Mille Lacs fishery and ecosystem characteristics. (A) Population size of age-3 and older walleye, estimated from statistical catch at age (SCAA) model. (B) Total walleye kill (recreational harvest, hooking mortality, and tribal harvest), estimated from the SCAA model. (C) Catch per net night from assessment gill nets of northern pike and smallmouth bass, two potential predators and/or competitors of walleye. (D) Median Secchi depth with 95% quartiles (data collected May–September by Minnesota Department of Natural Resources and Pollution Control Agency). (E) Median total phosphorus levels with 95% quantiles (data collected May–September by the Mille Lacs Band of Chippewa and the Minnesota Pollution Control Agency, and downloaded from the Water Quality Portal: https://www.waterqualitydata.us/portal/). (F) Mean summer (July–August–September) air temperatures based on interpolated topoclimatic daily air temperatures: https://catalog.data.gov/dataset/topowx-topoclimatic-daily-air-temperature-dataset-for-the-conterminous-united-states. Note that zebra mussels were discovered in 2005.

Starting from observed time series of the walleye population, TOHA, and predators, we estimated the parameters b_i of (2a) and (2b), as well as the standard deviation of model errors, by maximum likelihood. We examined residuals from the model fits to assess that model errors were approximately normally distributed and uncorrelated in time. We then estimated errors of the b_i by bootstrapping, using 10,000 random permutations of residuals with replacement (Efron and Tibshirani 1993). We then computed a population of bootstrap estimates of the SOS for specified values of TOHA or predators.

An estimate of the SOS consists of a pair of numbers, F_s and x_s, representing the maximum fishing mortality with positive population growth and the corresponding population size, respectively. We estimated the boundaries of the SOS by fitting the model to observed time series, solving the model for the upper bound of the SOS, and estimating errors of model parameters and the SOS by nonparametric bootstrapping. 90% confidence intervals (CIs) for F_s and x_s were approximated by estimating the 95% and 5% quantiles from values estimated from the 10,000 bootstrapped parameter sets. In a small number of cases, bootstrapped parameter sets yielded negative values for the SOS. In these cases, we set the SOS to zero. Maximum safe harvest at the SOS (F_s) and its CI were compared to total walleye kill in Mille Lacs to assess whether the fishery was overharvested based on the SOS estimates. These differences in harvest were also compared to change in estimated population size in the following year to examine whether years in which walleye were overharvested were followed by population declines.

Results

Thermal–optical habitat area for walleye in Mille Lacs declined over time (Fig. 3). Optical habitat area was most widespread in 1988 and 1999, when 15% of potential habitat area fell within preferred optical conditions. By contrast, optical habitat area was most restricted in 1997, when only 3% of habitat area was optically suitable. Thermal habitat area remained relatively constant over the same time period (Fig. 3). Thermal–optical habitat area declined over time, driven by changes in optical habitat area.

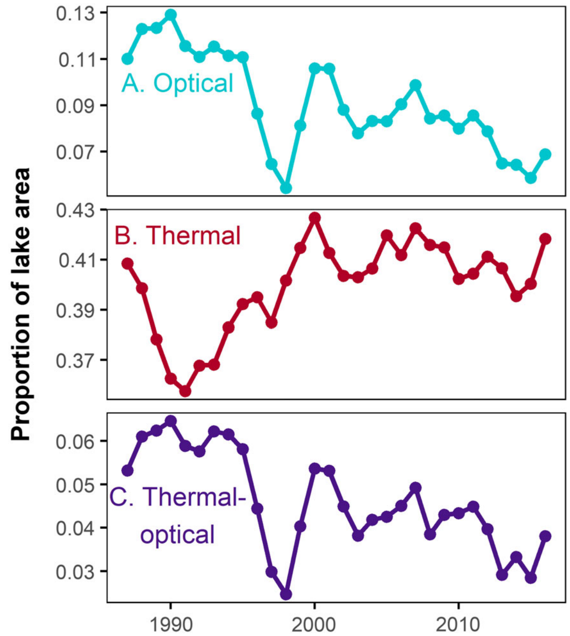

Fig. 3. Three-year moving average of walleye habitat, in terms of (A) optical (6-68 lux), (B) thermal (11–25°C), and (C) thermal–optical (both 6-68 lux and 11–25°C) habitat in Mille Lacs. Habitat metrics are shown as proportion of total available lake benthic area over time.

Thermal–optical habitat area was most restricted in 1997, and most available in 1988, 1993, and 1999 when over 7% of potential habitat area fell within preferred light and temperature ranges.

The walleye model without predators fit the data slightly better than a model containing predator abundance (AIC [predators] = 97.49; AIC [no predators] = 95.69). Here, we present results for the model without predators; see Appendix S2 for results of the model including predators. The walleye population model was able to recreate population trends (Appendix S2: Fig. S1). The autoregressive parameter and the effect of TOHA on carrying capacity were both positive (Appendix S2: Table S1). Maximum safe harvest at the SOS boundary (F_s) was positively and non-linearly related to TOHA (Fig. 4). Population size at the SOS boundary (x_s) was also positively related to TOHA (Appendix S2: Fig. S2). Small changes in habitat led to relatively large changes in safe harvest level—for example, when TOHA was 6.5% of lake area, maximum safe harvest was approximately 430,000 walleye. If

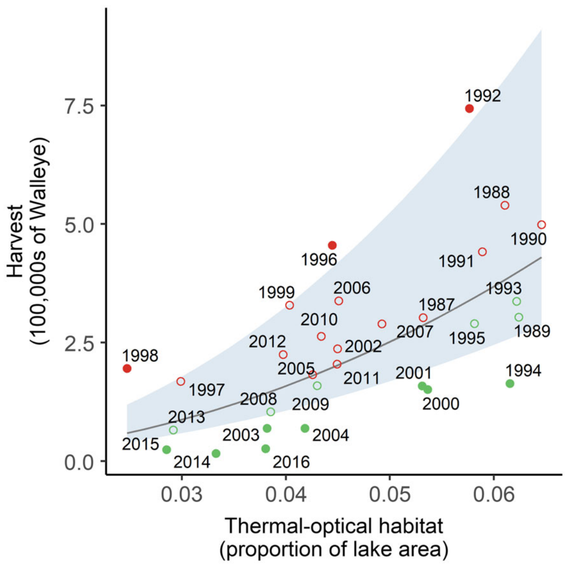

Fig. 4. Walleye harvest (in 100,000s of walleye) as a function of thermal–optical habitat area. Maximum safe harvest at the safe operating space across a theoretical gradient of habitat values estimated from maximum likelihood parameter estimates (black line) and 90% confidence intervals (CIs) estimated from 10,000 bootstrapped parameter sets (gray band) based on the SOS model. Walleye kill from 1987 to 2016 is also shown as a function of estimated thermal–optical habitat in each year (three-year moving averages). Colored points represent walleye harvest relative to the maximum safe harvest generated from the SOS model (red, harvest exceeded safe harvest; green, harvest was less than safe harvest). Filled circles represent years in which actual harvest fell outside the 90% CIs of safe harvest estimated by the SOS model.

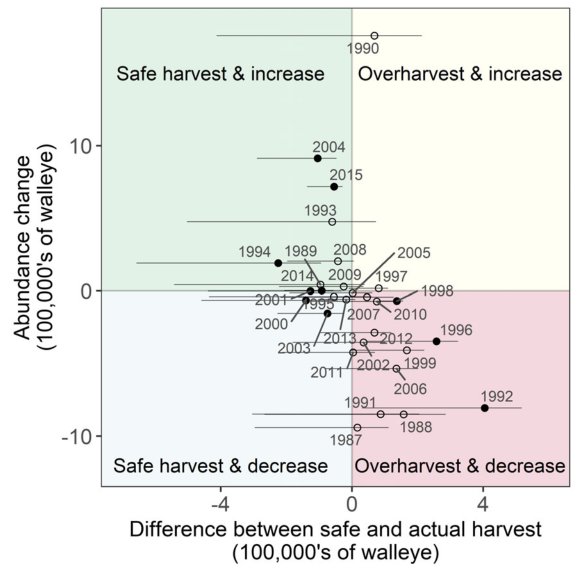

Fig. 5. Walleye harvest relative to estimated maximum safe harvest (x-axis) versus change in walleye abundance the following year (y-axis). Quadrants indicate years where the population was overharvested and declined (red), overharvested and increased (yellow), harvested within safe limits and increased (green), and harvested within safe limits and decreased (blue). Years are harvest years. Lines are 90% confidence intervals (CIs) of the x-axis values, representing uncertainty in safe harvest levels. Filled circles represent years in which actual harvest fell outside (either above or below) the 90% CIs of safe harvest estimated by the SOS model.

habitat area declined by half (TOHA = 3.2%), maximum safe harvest dropped to less than a quarter of peak values to under 100,000 walleye. Actual harvest exceeded the maximum likelihood predicted safe harvest in 16 of 30 yr, and exceeded upper bootstrapped 90% CIs in 3 yr (1992, 1996, and 1998). In recent years (2013–2016), harvest has been well below estimated safe harvest levels. Walleye abundance declined following 14 of the 16 yr in which actual harvest exceeded the maximum safe harvest estimated by the SOS model (Fig. 5). Population increases were observed in 10 yr out of the time series, and in 8 of these years, the previous years' harvest fell below estimated safe levels.

Discussion

The SOS for fisheries defines the range of conditions that maintains fish biomass and harvest at acceptable levels even as the environment changes (Carpenter et al. 2017). We identified the SOS for walleye populations in Mille Lacs as a function of habitat (TOHA) and walleye harvest in the first empirical test of the SOS concept applied to the management of harvested resources of which we are aware. Walleye habitat area in Mille Lacs declined over the past several decades, with important implications for fisheries management. The historical range of TOHA resulted in estimated safe walleye harvest levels that varied by nearly an order of magnitude. Walleye mortality in Mille Lacs exceeded mean safe levels based on TOHA in about half of the past 30 yr, though uncertainty surrounding these safe harvest estimates is high. In the majority of cases where harvest exceeded estimated safe levels, the walleye population declined in the following year. Similarly, population increases were more likely to occur following years in which harvest fell within estimated safe levels. The major exception to these patterns occurred following harvest year 1990, when the walleye population increased in 1991 due to much higher than average recruitment to the fishery in spite of overharvest. The walleye population also declined in five years for which harvest fell within safe levels (blue quadrant in Fig. 5), although the magnitude of these decreases was small, indicating other sources of mortality not accounted for in our analysis. While TOHA and harvest cannot explain all variation in walleye populations, accounting for TOHA in harvest decisions makes harvest less risky and more likely to stay within the SOS.

In response to observed walleye population declines, walleye mortality has been well below estimated safe harvest levels in recent years (2013–2016). Based on our population model incorporating TOHA, such precautionary management should allow the walleye population to increase, depending on future habitat availability. Note that maximum safe harvest levels and population size at SOS are equilibrium values for a fixed TOHA value (x-axis in Fig. 4) and do not account for annual dynamics of TOHA. Furthermore, our model does not account for all potential drivers of walleye population abundance, such as population, food web, or ecosystem productivity changes associated with invasive zebra mussels (Irwin et al. 2016) or spiny water flea (Strecker et al. 2011) beyond what is captured by changing water clarity, and therefore may overestimate the walleye production that could currently be supported. Continued precautionary management and monitoring will help elucidate whether changes in TOHA are the main driver of walleye declines.

Increasing water clarity was the main driver of changing TOHA. Several mechanisms could account for this increase. Total phosphorus declined from 1992 to 2005–2013, and improvements to septic systems and land use around the lake may have played a role (Heiskary and Egge 2016). Zebra mussels increase water clarity (Higgins and Vander Zanden 2010) and hence optical habitat area (Geisler et al. 2016), but zebra mussels were discovered in Mille Lacs in 2005 and cannot explain the observed increase in water clarity in the 1990s. Water clarity peaked in 2013, suggesting that zebra mussels may have further increased water clarity once they established. Thermal habitat area was relatively unaffected by increasing temperatures; Mille Lacs water temperatures exceeded 25°C in only 12 days of the 30 yr modeled here. However, changes in thermal habitat as defined by optimal growth conditions may not correlate with changes in fish populations. For example, increasing temperatures are associated with walleye declines in inland lakes (Robillard and Fox 2006, Hansen et al. 2017), despite increased walleye thermal habitat area in most lakes as climate warms (Fang et al. 2004). As the climate continues to warm, the number of days per year exceeding walleye thermal tolerance will increase and may negatively influence survival and growth of walleye in the future.

The response of TOHA to changing conditions depends on lake characteristics including morphometry, historical baseline, and stratification, although on average across all lakes TOHA is optimized at Secchi depths of 2 m (Lester et al. 2004). Mille Lacs is shallow and well-mixed lake, and historic Secchi depths were around the optimum value of 2 m. These factors increase sensitivity to increased water clarity and likelihood of impacts to walleye (Geisler et al. 2016). The trajectory of Mille Lacs in terms of ecosystem and fish community changes appears to be similar to what has been documented in Lake Oneida (New York, USA), another high-profile walleye fishery which has undergone dramatic changes in recent decades (Irwin et al. 2016), suggesting that these dynamics may not be unique. Still, other lakes with more complex bathymetries and different trophic status may respond differently to changing conditions.

Lakes with more TOHA support higher walleye biomass and harvest (Christie and Regier 1988, Lester et al. 2004, Tunney et al. 2018), although changes in TOHA over time have rarely been quantified or linked directly to walleye abundance (but see Chu et al. 2004, Jones et al. 2006). Water clarity and TOHA affect walleye populations through a number of pathways.

Walleye are more active in low-light conditions (Ryder 1977), and increased water clarity is associated with a shift from feeding during the day in turbid water to crepuscular or nocturnal feeding in clear water (Ali et al. 1977). Recent research has also demonstrated that walleye populations in lakes with low water clarity can access multiple prey sources and achieve higher biomass compared to lakes with high water clarity (Tunney et al. 2018). As water clarity increases and TOHA decreases, walleye may be restricted to offshore and deepwater habitats throughout most daylight hours. If energy resources in these habitats are limiting (as is likely to be the case in a system invaded by zebra mussels, Higgins and Vander Zanden 2010), populations are likely to be negatively affected by increasing water clarity. Understanding the mechanisms through which changes in water clarity affects walleye behavior, growth, and population dynamics and how such responses differ among lakes is a fruitful area of future research.

Successful fisheries management requires accounting for climate change and other global and regional stressors (Paukert et al. 2016). Sustainable harvest policies can differ substantially as ecosystem productivity changes (Walters et al. 2008). Changes in habitat area can alter population growth rates such that harvest levels that were once sustainable are no longer so (Carpenter et al. 2017). Our results suggest that altering harvest in response to changing conditions may allow Mille Lacs to retain its function as a walleye fishery. Our model estimates safe harvest levels as a function of walleye stock size and TOHA averaged over the previous three years, and could be run annually to estimate safe harvest. Continued monitoring of water clarity and temperature is relatively inexpensive and is already a part of standard monitoring of Mille Lacs and many other lakes; these data can be used to adjust harvest in response to environmental changes. Of course, a management regime that adjusts harvest based on environmental changes will require flexible structures and institutions that can adapt to change (Green et al. 2017), as well as a commitment to sustaining walleye populations over the long term. Accepting harvest reductions is socially and politically difficult, and will require coordination, communication, and collaboration among stakeholders, policy makers, and scientists (i.e., adaptive governance; sensu Folke et al. 2005). However, under rapidly changing conditions, the potential for exploitation is constrained and reductions in harvest can facilitate adaptation (Roberts et al. 2017). Our results, like all models fit to empirical data, are bounded by the range of variability in our dataset and the assumptions in our model. Parameter estimates and management implications may change if critical variables move outside the range we have previously observed. Therefore, sustained monitoring is essential for managing walleye and adapting to rapid and uncertain ecosystem change.

Theories of global change suggest the need for approaches based on a SOS for living resources, whereby harvest or other local variables are adjusted to compensate for large-scale changes in climate or other drivers (Scheffer et al. 2015, Carpenter et al. 2017). This study uses field observations to estimate the SOS, explain changes in walleye stocks in relation to the SOS, and suggest local changes in harvest that could sustain a valuable walleye stock in its SOS for the long term. We thereby demonstrate empirically a general approach that could be used to sustain diverse living resources in a time of extensive long-term environmental change (USGCRP 2018).

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Literature Cited

Akaike, H. 1973. Information theory as an extension of the maximum likelihood principle. Pages 267–281 *in* 2nd International Symposium on Information Theory. Akademiai Kiado, Budapest, Hungary.

Ali, M. A., and M. Anctil. 1977. Retinal structure and function in the walleye (*Stizostedion vitreum vitreum*) and Sauger (*S. canadense*). Journal of the Fisheries Board of Canada 34:1467–1474.

Ali, M. A., R. A. Ryder, and M. Anctil. 1977. Photoreceptors and visual pigments as related to behavioral responses and preferred habitats of perches (*Perca* spp.) and pikeperches (*Stizostedion* spp.). Journal of the Fisheries Research Board of Canada 34:1475–1480.

Carpenter, S. R. 2002. Ecological futures: building an ecology of the long now. Ecology 83:2069–2083.

Carpenter, S. R., et al. 2017. Defining a safe operating space for inland recreational fisheries. Fish and Fisheries 18:1150–1160.

Carpenter, S. R., E. H. Stanley, and M. J. Vander Zanden. 2011. State of the world's freshwater ecosystems: physical, chemical, and biological changes. Annual Review of Environment and Resources 36:75–99.

Christie, G. C., and H. A. Regier. 1988. Measures of optimal thermal habitat and their relationship to yields for four commercial fish species. Canadian Journal of Fisheries and Aquatic Sciences 45:301–314.

Chu, C., C. K. Minns, J. E. Moore, and E. S. Millard. 2004. Impact of oligotrophication, temperature, and water levels on walleye habitat in the Bay of Quinte, Lake Ontario. Transactions of the American Fisheries Society 133:868–879.

Efron, B., and R. J. Tibshirani. 1993. An introduction to the bootstrap. Chapman and Hall, New York, New York, USA.

Fang, X., H. G. Stefan, J. G. Eaton, J. H. McCormick, and S. R. Alam. 2004. Simulation of thermal/dissolved oxygen habitat for fishes in lakes under different climate scenarios: Part 1. Cool-water fish in the contiguous US. Ecological Modelling 172:13–37.

Folke, C., T. Hahn, P. Olsson, and J. Norberg. 2005. Adaptive governance of social-ecological systems. Annual Review of Environment and Resources 30:441–473.

Geisler, M. E., M. D. Rennie, D. M. Gillis, and S. N. Higgins. 2016. A predictive model for water clarity following dreissenid invasion. Biological Invasions 18:1989–2006.

Green, A. J., et al. 2017. Creating a safe operating space for wetlands in a changing climate. Frontiers in Ecology and the Environment 15:99–107.

Hansen, G. J. A., J. W. Gaeta, J. F. Hansen, and S. R. Carpenter. 2015. Learning to manage and managing to learn: sustaining freshwater recreational fisheries in a changing environment. Fisheries 40:56–64.

Hansen, G. J. A., J. S. Read, J. F. Hansen, and L. A. Winslow. 2017. Projected shifts in fish species dominance in Wisconsin lakes under climate change. Global Change Biology 23:1463–1476.

Heiskary, S, and L. Egge. 2015. A review of Secchi transparency trends in Minnesota lakes. Minnesota Pollutional Control Agency Internal Report wq-S2-08. https://www.pca.state.mn.us/sites/default/files/wq-s2-08.pdf

Higgins, S. N., and M. J. Vander Zanden. 2010. What a difference a species makes: a meta-analysis of Dreissenid mussel impacts on freshwater ecosystems. Ecological Monographs 80:179–196.

Hipsey, M. R., et al. 2019. A General Lake Model (GLM 3.0 for linking with high-frequency sensor data from the Global Lake Ecological Observatory Network (GLEON). Geoscientific Model Development 12:473–523.

Irwin, B. J., L. G. Rudstam, J. R. Jackson, A. J. VanDeValk, and J. L. Forney. 2016. Long-term trends in the fish community of Oneida Lake: Analysis of the zebra mussel invasion. Pages 375–396 *in* L. G. Rudstam, E. L. Mills, J. R. Jackson, and D. J. Stewart, editors. Oneida Lake: Long-term dynamics of a managed ecosystem and its fishery. American Fisheries Society, Bethesda, Maryland, USA.

Jones, M. L., B. J. Shuter, Y. Zhao, and J. D. Stockwell. 2006. Forecasting effects of climate change on Great Lakes fisheries: models that link habitat supply to population dynamics can help. Canadian Journal of Fisheries and Aquatic Sciences 63:457–468.

Lester, N. P., A. J. Dextrase, R. S. Kushneriuk, M. R. Rawson, and P. A. Ryan. 2004. Light and temperature: key factors affecting walleye abundance and production. Transactions of the American Fisheries Society 133:588–605.

Minnesota Department of Natural Resources (MNDNR). 2018. Infested Waters List. https://www.dnr.state.mn.us/invasives/ais/infested.html

Minnesota v. Mille Lacs Band of Chippewa Indians. 1999. (97-1337) 526 u.S. 172 https://www.law.cornell.edu/supct/html/97-1337.ZS.html

Paukert, C. P., B. A. Glazer, G. J. A. Hansen, B. J. Irwin, P. C. Jacobson, J. L. Kershner, B. J. Shuter, J. E. Whitney, A. J. Lynch. 2016. Adapting inland fisheries management to a changing climate. Fisheries 41:374–384.

Pollock, K. H., C. M. Jones, and T. L. Brown. 1994. Angler survey methods and their application in fisheries management. American Fisheries Society Special Publication 25, Bethesda, Maryland, USA.

R Core Team. 2017. R: a language and environment for statistical computing. Foundation for Statistical Computing, Vienna, Austria.

Reeves, K. A., and R. E. Bruesewitz. 2007. Factors influencing the hooking mortality of walleyes caught by recreational anglers on Mille Lacs, Minnesota. North American Journal of Fisheries Management 27:443–452.

Roberts, C. M., et al. 2017. Marine reserves can mitigate and promote adaptation to climate change. Proceedings of the National Academy of Sciences 114:6167–6175.

Robillard, M. M., and M. G. Fox. 2006. Historical changes in abundance and community structure of warmwater piscivore communities associated with changes in water clarity, nutrients, and temperature. Canadian Journal of Fisheries and Aquatic Sciences 63:798–809.

Ryder, R. A. 1977. Effects of ambient light variations on behavior of yearling, subadult, and adult walleyes (*Stizostedion vitreum vitreum*). Journal of the Fisheries Research Board of Canada 34:1481–1491.

Scheffer, M., et al. 2015. Creating a safe operating space for iconic ecosystems. Science 347:1317–1319.

Schmalz, P. J., A. H. Fayram, D. A. Isermann, S. P. Newman and C. J. Edwards. 2011. Harvest and exploitation. Pages 375–402 *in* B. A. Barton, editor. Biology, management, and culture of walleye and sauger. American Fisheries Society, Bethesda, Maryland, USA.

Schmalz, P. J. and M. Treml. 2014. Mille Lacs walleye statistical kill at age model report: fishing season 2014. Minnesota Department of Natural Resources Internal Report. https://figshare.com/s/f6d60ce448f4b3458553

Strecker, A. L., B. E. Beisner, S. E. Arnott, A. M. Paterson, J. G. Winter, O. E. Johannsson, and N. D. Yan. 2011. Direct and indirect effects of an invasive planktonic predator on pelagic food webs. Limnology and Oceanography 56:179–192.

Tunney, T. D., K. S. McCann, L. Jarvis, N. P. Lester, and B. J. Shuter. 2018. Blinded by the light? Nearshore energy pathway coupling and relative predator biomass increase with reduced water transparency across lakes. Oecologia 186:1031–1041.

USGCRP. 2018. Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II. in Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart, editors. U.S. Global Change Research Program, Washington, D.C., USA. https://doi.org/10.7930/NCA4.2018

Vandenbyllaardt, L., F. J. Ward, C. R. Braekevelt, and D. B. McIntyre. 1991. Relationships between turbidity, piscivory, and development of the retina in juvenile walleyes. Transactions of the American Fisheries Society 120:382–390.

Venturelli, P., J. R. Bence, T. O. Brenden, N. P. Lester and L. G. Rudstam. 2014. Mille lacs walleye blue ribbon panel data review and recommendations for future data collection and management. Report submitted to the Minnesota Department of Natural Resources.

Walters, C. J. 1987. Nonstationarity of production relationships in exploited populations. Canadian Journal of Fisheries and Aquatic Sciences 44:s156–s165.

Walters, C. J., R. Hilborn, and V. Christensen. 2008. Surplus production dynamics in declining and recovering fish populations. Canadian Journal of Fisheries and Aquatic Sciences 65:2536–2551.

Walters, C. J., and S. J. D. Martell. 2004. Fisheries ecology and management. Princeton University Press, Princeton, New Jersey, USA.

Winslow, L. A., G. J. A. Hansen, J. S. Read and M. Notaro. 2017. A large-scale database of modeled contemporary and future projected water temperature data for 10,774 Michigan, Minnesota And Wisconsin lakes. Scientific Data 4: Article number: 1700

Supporting Information

Additional Supporting Information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/ecs2.2737/full

GEORGIA DEPARTMENT OF NATURAL RESOURCES WILDLIFE RESOURCES DIVISION

Fishing Forecast - Lake Burton

Fishing Forecast - Lake Burton

February 13, 2025

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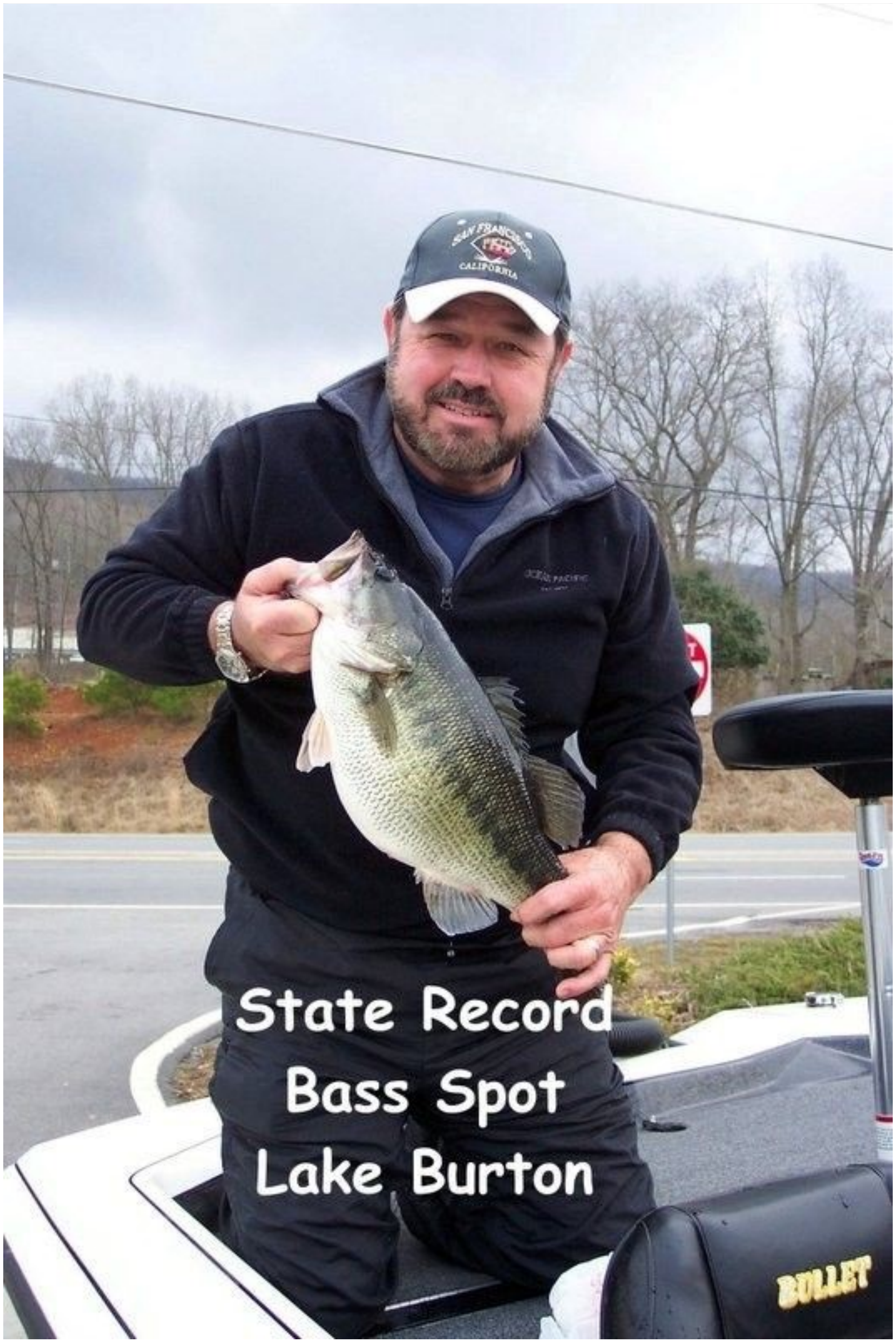
Overview

Lake Burton is a 2,775-acre reservoir located near the City of Clayton. This mountain reservoir features beautiful scenery and exquisite lakeside homes. Managed by the Georgia Power Company, this lake supports an excellent spotted bass fishery and is home to the current state record - a whopper caught in February 2005 that tipped the scales at 8 pounds, 2 ounces. In addition to spotted bass, anglers also enjoy catching largemouth bass, yellow perch and bream.



State records and fishing reports

Best Bets: Spotted Bass, Largemouth Bass

- Largemouth Bass
- Spotted Bass
- Brown Trout

Lake Burton - Largemouth Bass

Fish Identification Page

Prospect: Catch rates for Largemouth Bass in Lake Burton were consistent with past averages for the reservoir. The population's size structure predominately consists of individuals in the 8 - 16 inch range which generally fall between 1 - 3 pounds in total weight. While big bass might be harder to come by, there will be some lucky anglers who will land a few of Burton's trophies like the 8 pound bass caught a few years ago during GA-DNR's annual spring boat electrofishing sampling.

6 lb Largemouth Bass from Lake Burton

Technique: Largemouth bass in Lake Burton prey mostly on blueback herring and the trophy bass pictured above was feeding in a school of herring that were spawning against a rock wall during mid-April. Fishing with live herring is naturally the best bait, but soft-bodied jerk baits that mimic herring have a unique advantage over other artificial lures. Other proven tactics include drop-shotting with finesse worms, bouncing Carolina rigged worms or pig-and-jigs along points, humps, brushpiles and creek channels. Crankbaits and spinner baits attract strikes at certain times of the year.

During the fall and winter months, herring and crayfish account for the bulk of the bass' natural diet. Fishing with live herring, shiners or trout are effective cold weather baits, but pig & jig combinations are the best artificial bait. Anglers should always have a big swim bait ready in case sudden and spontaneous topwater activity erupts nearby.

In the springtime, slow rolling spinnerbaits and jerk baits in creek channels and around docks and trees are good approaches for catching bass in shallow water.

Target: Largemouth bass are structure oriented; therefore, anglers should target visible structure like fallen trees and boat house pilings as well as underwater topographic features like channel edges, points, humps and brushpiles. Largemouth bass are more abundant in the coves on the lower end of the lake, including Murray, Perrin and Cherokee Coves. The Murray Cove boat ramp is the closest access point to these areas.

During the spring months, largemouth bass will hold close to visible structure with overhead cover under which they build their spawning nests.

In the summer months, largemouth bass will feed on top in the early morning and evening hours. Cast big swim baits, a Spook or a Sammy into the surface frenzy. During the heat of the day, largemouth bass will hold up on top of structure in 20 to 30 feet of water along main lake points and the edge of creek channels. Drop-shot finesse worms on top of brushpiles in 20-30 feet of water can be very effective.

During the fall months, largemouth bass will actively feed at the surface over the open water near the back of most coves. Topwater lures and crank baits that mimic blueback herring are effective this time of year. A fall back strategy is to bounce crayfish imitations on the bottom along rocky points.

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Lake Burton - Spotted Bass

[Fish Identification Page]

Prospect: The Spotted Bass population of Lake Burton is stable and shows similar catch rates compared to last year's sampling efforts, with individuals around the 1 - 2 pound mark being abundant this year. Spots in Lake Burton typically top out around 6 pounds, but a few fish weighing up to 8 pounds have been caught. The 6 pound Spotted Bass pictured below was caught by GA-DNR staff during a past annual spring population survey.

6 lb Spotted Bass from Lake Burton

Technique: February and March are prime months to catch big bass in Lake Burton. Pig-and-jig combinations, drop shot finesse worms and live herring or trout are excellent bait choices during the winter months. Anglers should target downed trees and rocky points, but fishing along the face of dam can also be productive on warm winter days.

April and May are the best months to catch high numbers of spotted bass. Jerk baits in herring color patterns, floating worms and spinnerbaits are effective this time of year when fished around the corners of boat docks and downed trees. Finesse worms also are effective when rigged Carolina style and dragged across rocky bottoms.

After the spawning season, spotted bass will chase big topwater lures near points and over humps in open water. This technique works best around dawn and dusk. During the day, try drop-shoting finesse worms or down lining live herring on rocky points or brush piles in 20-30 feet of water, especially on the lower half of the lake.

When the leaves change into their fall colors, spotted bass will aggressively feed on blueback herring in open water and in the creek mouths. Pulling planer boards or live lining blueback herring near the surface is the best way to catch high numbers of spotted bass during the fall. Among artificial lures, a weighted fluke or white crankbait are the best baits to cast on main lake points. If that pattern is not working, then switch to drop-shoting finesse worms into brushpiles, vertical jigging with spoons on rocky points or flipping a pig-and-jig into downed trees. Fishing on the bottom with live crayfish and nightcrawlers are also good live bait choices for fishing bottom structure during the fall months.

Target: For most of the year, spotted bass roam the open waters of Lake Burton in search of their favorite food - blueback herring. If you can find a school of herring, then spotted bass will likely be nearby; however, knowing their predictable seasonal tendencies will help narrow your search area.

During cold weather when the water temperature is in the mid-40s, large schools of adult herring hold tight to the face of the dam and that's where you will find the trophy spots. Drifting live herring around the face of the dam is very effective during cold weather but the bite can be slow. If spots are not willing to take your bait, then fish the rocky points and humps at the mouth of Murray Cove or the downed trees near Jones Bridge.

In April and May, spotted bass move into shallow water nesting areas located on rocky banks along the main shoreline as well as around boat docks located on steep, rocky shorelines. Cast toward these structures using jerk baits, floating worms or plastic lizards. Other effective techniques that work well on rocky banks during the spring are a wacky-rigged Senko worm and Carolina-rigged finesse worms.

Warming water temperatures from June to September motivate spotted bass to follow the schools of herring offshore into deeper open water. At dusk and dawn, spots will chase bait on the surface over main lake points and humps but during the day, they retreat into the cover of brushpiles that are scattered along the bottom of the lake in 15 to 30-feet of water.

In the fall months, spotted bass frequent rocky points in the major cove arms to feed on crayfish or yellow perch and will frequently cross over rocky points in search of a school of young, three-inch long blueback herring. Points and creeks in Mocassin, Dicks and Timpson Coves hold good numbers of fish from October to December.

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Lake Burton - Brown Trout

Fish Identification Page

Prospect: Lake Burton has the unique capacity to support a reservoir trout fishery and can produce some really big fish, as seen in the picture below. Back in 2023, Brown Trout stocking efforts were restarted in Burton with catchable-sized Brown Trout raised nearby at the state hatchery and then stocked out during the fall. This influx of new fish should raise catch rates and improve conditions for anglers hoping to land a trout out of Burton.

Lake Burton record Brown Trout weighing 11 lb 14 oz (2018).

Technique: The best bait for catching brown trout in Lake Burton is live blueback herring; however, trout will also take trolling spoons and small crankbaits all year long. From late-winter into spring, trout will frequent the shallow backwaters of the major coves and cruise along rocky seawalls feeding on blueback herring.

In the summer months, trolling very slowly with live herring or spoons on the lower half of the lake over the river channel at depths from 30 to 60-feet is generally the best approach.

From October to December, anglers should cast in-line spinners around the dam, Murray's Cove boat ramp, and around the Moccasin Creek boat ramp to catch recently stocked trout.

Target: In the winter months, most trout will be found near the dam but some fish also find their way to the upper end of the lake around Jones Bridge.

During the spring, trout will move closer to the backs of coves and feed on the surface during early morning. Moccasin Cove is a great starting place to look but also look at Murrays Cove all the way to the dam.

During the summer months, trout move to deeper, cooler water on the lower end of the lake. Troll along the river channel from the safety marker located on the main lake near Moccasin Cove and work your way toward the dam. In October and November, trout can be widely scattered around the lake. Recent stockers will be abundant around the dam and near the boat ramps in Murrays Cove and Moccasin Cove. Anglers may also want to fish the mouth of other creek channels like Timpson and Dicks Creeks, in hopes of catching a trophy brown that is making its way into the shallow streams to spawn.

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Additional Information

Lake Burton 2024 Angler Card

Yellow perch fishing has improved over the last two years and trophy-sized fish, like the one pictured below, are being caught in early-spring. A few walleye occasionally show up in an angler's live well.

2 lb Yellow Perch from Lake Burton

Free boat launching facilities are available at Moccasin Creek next to Lake Burton Trout Hatchery and Moccasin Creek State Park located on Highway 197 North, as well as at Georgia Power's Murray Cove Boat Ramp located on Murray Cove Road. For a small fee, boats can be launched at two private marinas located at La Prades Marina on Highway 197 North and at Timpson Cove Marina located on Charlie Mountain Road.

A Lake Burton trout fishing guidebook is available at no cost on the Wildlife Resources Division web site. This guide discusses tactics and offers expert tips for fishing Lake Burton in spring, summer, fall and winter.

Lake level and other information about Lake Burton is available on the Georgia Power website at http://georgiapowerlakes.com/northgeorgialakes/

Contact Information:

Georgia DNR (770) 535-5498

Georgia Power Company (706) 746-1450

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GEORGIA
DEPARTMENT OF NATURAL RESOURCES
WILDLIFE RESOURCES DIVISION

Fishing Forecast - Lake Rabun

Fishing Forecast - Lake Rabun

February 13, 2025

Esri, NASA, NGA, USGS, FEMA | Esri, TomTom, Garmin, SafeGraph, GeoT... 2,000 ft Powered by Esri

Overview

Lake Rabun is an 834-acre lake that is in the Northeast Georgia mountains near the City of Clayton and just a few miles downstream of Lake Burton. This mountain reservoir is long and narrow and most of the steep, rocky shoreline is dotted with boathouses and beautiful summer homes. The upper two miles of the lake seems more like a narrow river, which becomes shallow and rocky near the headwaters just below Nacoochee Dam. Spotted bass, largemouth bass, walleye, bluegill and shellcrackers are the favorite fish species targeted by local anglers.

Contact Information: Georgia Power: (706) 746-1450; DNR Office: (770) 535-5498

State records and fishing reports

Best Bests: Largemouth Bass, Spotted Bass, Bream, and Walleye

- Largemouth Bass
- Spotted Bass
- Bream
- Walleye

Lake Rabun - Largemouth Bass

Largemouth Bass

Fish Identification Page

Prospect: Spring sampling showed a Largemouth Bass abundance similar to the average of previous years, with individuals mostly hovering around the 8 – 16 in. size range. Largemouth Bass in the 1 – 3 pound range continue to be numerous and are eager to be caught by anglers on hook and line. Larger individuals such as the 7-pounder pictured below or the multiple 8-pounders sampled in recent years all go to show that trophy fish are just waiting to be hooked in this reservoir.

7 lb Largemouth Bass from Lake Rabun

Technique: Bass in Lake Rabun will take advantage of any opportunity to grab a blueback herring, so fishing with live herring will usually out-catch manufactured baits. When selecting artificial lures, anglers should choose designs that look and move like a distressed herring.

During the spring and fall months, cast a big-bladed spinner bait with a white skirt or a 3/8-oz jighead tipped with a fluke around hard structures like boat docks, downed trees, and rock sea walls. When fast moving subsurface lures are not attracting strikes, drop shot finesse worms into brush piles or use a Carolina rig to bounce soft plastics along creek channels, ledges and points.

When the water temperature drops below 55 degrees, largemouth bass will hold tight to woody structure and rocks in 5 to 15-feet of water. Bass tend to be more active in the late afternoon after the sun has warmed up the water a bit. Under these conditions, floating a live shiner under a cork or pitching a pig-and-jig with a crayfish trailer are effective tactics.

Target: The highest catch rates for largemouth bass come from the "Big Basin" area on the upper end of the lake. Anglers should target the boat docks, downed trees and small creeks and cove pockets scattered around the shoreline in this area. Largemouth bass also seem relatively abundant in the cove pockets and creek channels from Hall's Marina to the dam.

In the summer months, look for largemouth bass in 20 to 30 feet of water along main lake points and in creek channels in the mid-lake section. During the fall months, largemouth bass will actively feed at the surface over open water during the early morning and evening. The river channel on the upper end of the lake within the vicinity of the U.S. Forest Service Ramp downstream to the "Big Basin" is the best area to catch bass on the surface during the fall months.

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Lake Rabun - Alabama Spotted Bass

Spotted Bass

Prospect: Should be another great year for catching Spotted Bass out of Lake Rabun. Catch rates are similar to last year and desirable-sized individuals continue to remain in high numbers. Anglers should expect to see mostly 1 – 3 pound fish in their live wells with the chance for even bigger spots, like the 6-pounder pictured below, still remaining an exciting possibility.

6 lb Spotted Bass from Lake Rabun

Technique: Spotted bass are generally aggressive feeders that take a variety of natural and artificial baits. In the winter months, spotted bass feed less frequently but they will still take advantage of any opportunity to grab a blueback herring that comes within striking distance. Your best bait choices during the cold weather months are live herring or minnows fished around woody structure. Slow moving pig & jig combos tipped with a crayfish trailer can also be effective at times, especially when fished around rocky bottoms and main lake points.

In April and May, spotted bass spawn in shallow water ranging from 5 to 15-feet deep. Soft-bodied jerk baits, shallow-running plugs, floating worms, and plastic lizards are effective when cast near visible structures where bass nests are visible. Live nightcrawlers, crayfish and shiners are effective natural bait alternatives when fish are holding tight to their nests and seem reluctant to take an artificial lure.

In the summer months, spotted bass will roam the open waters in search of schooling blueback herring. These schools are often located at depths from 20 to 30-feet deep. Anglers should use their sonar to locate brushpiles in this depth zone and then methodically work each brushpile with drop shot tactics.

Target: In the winter months, spotted bass hold close to visible structure. Points and cove pockets in the "Big Basin" area and near the dam hold the largest concentrations of spotted bass during the winter. Target fallen trees, boat houses, rock walls and brushpiles. On warm afternoons, anglers should also fish along the face of the dam using live herring or herring-type crankbaits or even Alabama rigs.

During April and May, spotted bass seek rocky banks with overhead cover to build their spawning nest. Fallen trees and the corners of boat houses are favored spawning areas. The "Big Basin" area and the area from Hall's Marina downstream to the dam support the highest concentrations of spotted bass.

As the water temperature cools during the fall months, schools of spotted bass will aggressively feed at the surface on small blueback herring. This is a great time to fish with small topwater baits, Alabama rigs or live-line with blueback herring. Schooling bass are most abundant in the narrow section of the river in the upper end of the lake between the U.S. Forest Service boat ramp downstream to the "Big Basin" area.

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Lake Rabun - Walleye

Walleye

Fish Identification Page

Prospect: Walleye numbers continue to remain somewhat low on Lake Rabun, with catch rates from fall gill net sampling showing similar values to those from the last few years. While this may not be ideal for catching Walleye in large quantities, the opportunity remains to land large individuals out of the reservoir like the one pictured below. Lake Rabun even has the bragging rights to the state record

Walleye, weighing in at 14 lb 2 oz.

6 lb Walleye from Lake Rabun

The state record walleye was caught from Lake Rabun in 2016 and weighed 14 lb 2 oz. This record fish is a testimony to Lake Rabun’s trophy walleye potential.

Technique: There are three seasonal patterns for catching walleye in Lake Rabun. During March, fish the shallow headwaters at dusk and dark with floating stick baits, chartreuse curly-tailed grub, shallow running crankbaits or nightcrawlers. During the day, fish the deeper sections of the lower river by dragging nightcrawlers along the bottom or by trolling crankbaits in perch, shad or crayfish color patterns.

From June to September, walleye transition to a summer pattern. In the summer, walleye migrate to deeper water near the dam and into coves in search of cooler temperatures. Troll crankbaits, live herring or drag nightcrawlers slowly along the bottom at depths near 30 feet. If you detect bottom structure on sonar, then fish the structure thoroughly using tactics similar to crappie fishing by working crappie minnows in and among its nooks and crannies.

When cooler water temperatures return in October and November, walleye switch to a fall pattern where they move onto shallow water points at night to feed on small bream and perch. During the day, walleye hang tight to the bottom in nearby deeper water where they can be caught with nightcrawlers and minnows using the summer tactics.

Target: During the spawning season, anglers can fish from the shoreline at Georgia Power's Nacoochee Park, which is located at the intersection of Low Gap Road and Seed Lake Road downstream of Nacoochee Dam. About an hour before sunset, start fishing at the Low Gap Road Bridge. As evening progresses, work your way upstream.

After the spawning season, walleye move down to the lower end of the lake. During the summer and fall months, troll the lower lake from Hall's Marina to the dam. Good electronics will help you identify schools of herring on which walleye are feeding. Be sure to cast nightcrawlers or herring into brushpiles as you encounter them. Walleye will be tucked under the branches, but will pop out to grab an easy meal.

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Lake Rabun - Bream

Bluegill Sunfish

Fish Identification Page

Prospect: Lake Rabun supports a fair number of quality-sized Bluegill, Redbreast Sunfish, and Redear Sunfish. Bluegill are the most abundant sunfish species in the reservoir and typically weigh between 1/4 - 1/2 pound. GA-DNR spring boat electrofishing sampling efforts collected a good array of individuals, but the trick for anglers will be landing the right filletable-size fish. Among these species, Redbreast Sunfish are the smallest and least abundant of the three, while Redear Sunfish are the largest and frequently reach weights over 1 pound.

Technique: Bluegills and redbreast readily take crickets, while the larger redear sunfish prefer red wigglers in deeper water. The best artificial lures for bream include small in-line spinner baits, like a Mepps Spinner or Rooster Tail, or small curly-tailed grubs. If you are into fly fishing, try casting rubber ants or spiders underneath overhanging branches during the early morning or evening.

Target: During the full moon in late-May or early-June, bream will build spawning nests on sandy flats where creeks flow into the lake. Their circular nests are generally visible from the surface and are the best place to target bream in the springtime. Bank fishing opportunities are available on the upper end of the lake at the U.S. Forest Service boat ramp and its two public fishing piers, but a $5 parking fee is required.

For the remainder of the year, bream will concentrate around boat docks, downed trees and rock walls. Anglers can usually find large numbers of bream under the shaded overhangs at Hall's Marina, which is located on the lower end of the lake. Dabble worms or crickets around the dock pilings that are covered in shade.

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Additional Information

Lake Rabun Angler Card 2024

Spring Boat Electrofishing

species	number sampled	% of total sample	catch rate (fish/hour)	average length (in)	average weight (lb)	lake record size (lb oz)
Bluegill	21	9%	4.2	6.3	0.2	1 lb 14 oz
Largemouth Bass	151	62%	30.2	11.8	0.8	12 lb 6 oz
Spotted Bass	70	29%	14.0	12.3	1.0	6 lb 2 oz

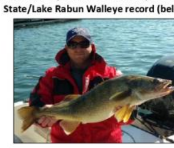
Fall Gill Netting

species	number sampled	% of total sample	catch rate (fish/net night)	average length (in)	average weight (lb)	lake record size (lb oz, * for state record)
Black Crappie	12	14%	1.5	12.0	0.9	2 lb 0.16 oz
Largemouth Bass	17	20%	2.1	12.4	0.9	12 lb 6 oz
Redbreast Sunfish	1	1%	0.1	6.1	0.1	-
Redear Sunfish	8	9%	1.0	9.6	0.5	2 lb 3 oz
Spotted Bass	29	33%	3.6	14.0	1.4	6 lb 2 oz
Walleye	1	1%	0.1	17.4	1.8	14 lb 2 oz*
Warmouth	2	2%	0.3	7.6	0.4	-
White Catfish	2	2%	0.3	12.0	0.9	-
Yellow Perch	3	3%	0.4	13.6	1.0	1 lb 8.8 oz

Fishing Prospects

species	SFI	prospect	summary
Black Crappie	34	Good	Lower catch rates but large individuals in the population
Largemouth Bass	40	Good	Similar catch rates to last year with fish averaging around 1-3 lb
Spotted Bass	43	Excellent	Similar catch rates to last year with fish averaging around 1-3 lb
Walleye	30	Fair	Low catch rates with some large individuals

Lake Rabun Spotted Bass record (above) and State/Lake Rabun Walleye record (below)



The Sport Fishing Index (SFI) assigns a numerical value for the status of each population. Please note that only species of angling interest sampled during this year are included in the tables above.

GEORGIA Department of Natural Resources Wildlife Resources Division

Lake Rabun 2023 Angler Card

A walleye fishing guidebook is available at no cost on the Wildlife Resources Division website here.

With funding and manpower provided by Georgia Power Company, several artificial structures were placed into Lake Rabun in 2018 on deepwater points on the lower end of the lake to attract bass, crappie and walleye. GPS coordinates for these sites are available.

More information about Lake Rabun is available from Georgia Power. The Georgia Power website is http://georgiapowerlakes.com.

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GEORGIA DEPARTMENT OF NATURAL RESOURCES WILDLIFE RESOURCES DIVISION Fishing Forecast - Lake Tugalo

Fishing Forecast - Lake Tugalo

February 13, 2025

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Overview

Lake Tugalo is a beautiful 600-acre lake formed by the Tallulah and Chattooga rivers. Owned and operated by the Georgia Power Company, Lake Tugalo lies on the Georgia-South Carolina border near the city of Clayton. The steep canyon walls and small waterfalls that surround the forested shoreline create unusual scenic beauty. To maintain the pristine aspects of this small reservoir, outboard motors are restricted to 25 horsepower. Both largemouth and spotted bass occur in good numbers in Lake Tugalo, but this unique reservoir also offers good fishing for walleye and yellow perch. In addition to a quality bream fishery consisting of large redbreast, bluegill and shellcrackers, Tugalo also provides seasonal opportunities to catch white bass and channel catfish.

Contact Information: Georgia Power: (706) 746-1450; DNR Office: (770) 535-5498.

State records and fishing reports

Best Bets: Largemouth Bass, Spotted Bass, Walleye, Yellow Perch, Redbreast Sunfish, Bluegill, Shellcrackers and White Bass

- Largemouth Bass
- Spotted Bass
- Walleye
- Yellow Perch
- White Bass
- Bream
- Catfish

Lake Tugalo - Largemouth Bass

Fish Identification Page

Prospect: Catch rates for Largemouth Bass in Lake Tugalo have remained high and stable over the course of the last few years, with this year continuing that pattern. Anglers will mainly catch bass in the 1 – 2 pounds weight range, but the chance for trophy-sized individuals still remains. The fish pictured below weighed in at 10 pounds and was collected during a past GA-DNR spring sampling event on the reservoir.

10 lb Lake Tugalo Largemouth Bass

Technique: From December through March, largemouth bass find shelter among the submerged branches of fallen trees that are scattered along Lake Tugalo's steep, undeveloped shoreline. Fishing the trees with Wacky-rigged worms, pig & jig combinations and live baits are effective cold water tactics.

During the spawning season (April and May), cast soft-bodied jerk baits, floating worms, spinner baits or plastic lizards around visible structure near the shore's edge. Slow rolling spinnerbaits in the creek channels is also an effective springtime tactic.

When water temperatures heat up in the summer months, look for quality-sized fish in the cooler headwater areas of the lake. Bouncing crayfish imitations or live nightcrawlers along the rocky bottom are effective baits for catching bass in these rocky, shallow water areas. Shallow running stickbaits in herring color patterns or jigs tipped with a curly-tailed grub can also be effective in the headwaters.

The transition into the cooler fall months pushes bass into the interior recesses of downed trees, especially on the upper end of the lake. Shad-imitating crankbaits, soft plastics and jigs are best bets in the fall. Anglers should also keep a watchful eye for surface feeding fish in the upper reaches of the lake and cast toward breaking fish with crankbaits and surface plugs.

Target: The shoreline of Lake Tugalo is very steep, undeveloped and dotted with fallen trees, which provide a haven for largemouth bass. The Chattooga River arm in the vicinity of South Carolina boat ramp is one of the best places to fish for bass during the spring and fall months. The upstream headwater areas on both river arms are the best places to fish for bass in the summer.

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Lake Tugalo - Spotted Bass

Fish Identification Page

Prospect: Lake Tugalo's steep, rocky shoreline provides favorable habitat for Spotted Bass. Spots have resided in the lake for more than a decade, but the population has not soared during this time frame as it has in other nearby reservoirs. This continues to hold true, with catch rates remaining low and most of the population being dominated by individuals bordering a pound or so in weight.

Largemouth Bass collected from Lake Tugalo in DNR bass surveys

Technique: Spotted bass will roam a wide area in search of their favorite food, which is blueback herring. White-bodied soft plastics or hard baits that imitate herring will likely attract the attention of a hungry spotted bass on the prowl.

Target: Spotted bass are more abundant in the Tallulah River arm of the lake. Anglers who want to target spotted bass are advised to start in the mid-section of the Tallulah River arm and fish toward the upper reaches of the gorge. Spotted bass orient to points and areas with large rocks. Spots will also be attracted to the deep side of the downed trees that are scattered around the shoreline. During the fall months, spots can be seen feeding on blueback herring over open water.

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Lake Tugalo - Walleye

Fish Identification Page

Prospect: Walleye are relatively abundant in Lake Tugalo, giving this reservoir the distinction as one of the best Walleye lakes in Georgia. This year was no different from the norm, having excellent catch rates with multiple individuals captured in each gill net. Most fish that anglers catch will be in the 2 - 3 pound range, though there are still a few trophies, like the one pictured below, that continue to roam the lake.

Technique: From March to early-April, several lure styles will attract a walleye bite in the flowing headwater areas of both river arms, including small crankbaits or stick baits in crayfish and herring patterns as well as a small jig-head tipped with a nightcrawler or curly-tailed grub. Use a slow but steady retrieve when bouncing the bait along the bottom. Be prepared for gentle resistance on the line, which indicates a strike, and maintain that steady retrieve. During daylight hours, anglers should bounce nightcrawlers on the bottom around downed trees in deeper water.

The summer heat forces walleye to migrate into the main body of the lake. Brushpiles and downed timber in 30 to 50-feet of water are the favorite summertime hideouts for Tugalo walleye. Using sonar, locate these areas on the Chattooga River arm and then slowly and patiently dabble nightcrawlers, minnows or jigs into every nook and cranny of the structure in hopes of enticing a gentle strike. If you suspect the walleye has taken the bait, allow plenty of time before setting the hook.

In the fall months, walleye often move into shallow water at night to feed on bluegill, yellow perch and blueback herring. Nightcrawlers, minnows and shad-imitating lures are effective this time of year. Walleye have a very light bite, so anglers new to walleye fishing should remain alert to slight movements in the line, which may indicate a strike.

Target: From March to mid-April, walleye congregate in the headwater areas of the Tugalo and Chattooga River arms. These areas are only accessible by boat. The Tugalo arm below the Power Plant is easier to fish during the non-generation periods, which usually occur from mid-morning to mid-afternoon. The Chattooga River arm maintains a steady flow all year. Anchoring in the slack water adjacent to the large cascade is the safest way to fish this fast water area, and it is well worth the effort because large concentrations of walleye are within casting distance of this spot.

From mid-April through June, anglers should fish on the bottom around downed trees along the upper half of the main lake. Cast nightcrawlers toward the bank and move it along the bottom very slowly.

The best catches of walleye occur on the lower half of the lake during the summer months. Use sonar to locate downed trees and structure on the bottom in 30 to 50-feet of water. Walleye will hide under these structures and wait to ambush their prey. Slowly and methodically drift nightcrawlers or jigs in and around these structures to entice a strike.

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Lake Tugalo - Yellow Perch

Prospect: A successful Yellow Perch fishery with trophy individuals also exists as a by-product of the Walleye fishery, with Walleye feeding on the perch to keep numbers low and allowing perch to achieve maximum growth and size. Due to this, Yellow Perch weighing multiple pounds have been caught, often nearing the state record of 2 lb 9 oz.

Techniques and Targets: The technique for catching yellow perch is simple. Thread a nightcrawler or small minnow onto a jighead and bounce it slowly across the bottom near blowdowns or creek channels. Seriously, this technique works year-round; however, the monster-sized fish are caught in late-winter before they spawn.

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Lake Tugalo - White Bass

Fish Identification Page

Prospect: White Bass are not overly abundant in Lake Tugalo, but a fishable population persists despite this. This year catch rates matched the average for prior sampling events and individuals were most commonly seen in the 1 - 2 pound range.

Anglers can expect reasonable success in the months of March and October if they want to target White Bass. In mid to late-March, they will migrate into the headwaters of both river arms to spawn. During the fall months, White Bass will feed on small Blueback Herring near the surface in the upper reaches of the Chattooga River arm of the lake.

Technique: During the spring months, a small curly-tailed grub on 4 lb test line with a #6 hook is all the tackle that is needed to catch these scrappy fighters. If fish seem to be holding a little deep, then change to in-line spinner baits, like a Mepps Spinner or Rooster Tail, or small curly-tailed grubs in white, yellow or chartreuse threaded onto a light-weight jig head. Small topwater plugs will generate strikes during the fall months when white bass are feeding on schools of small herring at the surface.

Target: During the springtime, anglers will find white bass in the upper portion of the Chattooga River. Start fishing where the river narrows down and fish upstream as far as motor boat access is possible. In the fall, look for breaking fish in the narrow section of the lake on the upper Chattooga River arm.

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Lake Tugalo - Bream

Fish Identification Page

Prospect: Bluegill, Redbreast Sunfish, and Redear Sunfish are plentiful in Lake Tugalo. Bluegill and Redbreast Sunfish in the 6 – 8 in. range are very common around downed timber and stream outlets in the upper half of the lake. Catch rates continue to be looking good for the coming year, with size structures for both populations having a high amount of keeper-sized individuals. Redear Sunfish are less abundant, but trophies weighing up to 3 pounds are caught each year along the steep, rocky banks near the South Carolina boat ramp.

Technique: Crickets and small spinners are effective baits for redbreast and bluegill. Cast around shallow water structure that is located in the small pockets and backs of coves. Fishing with red wigglers on slightly deeper rocky bottoms on the main shoreline is a more effective approach for targeting trophy shellcrackers.

Target: Fallen trees are abundant along the rugged, undeveloped shoreline of Lake Tugalo. The submerged tree trunks and branches provide a perfect hideout for bream that should be targeted by bream anglers. In addition, good numbers of bream reside in the many small creek mouths that drain into the lake.

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Lake Tugalo - Catfish

Lake Tugalo was once known by local anglers as a great catfish lake. However, as time went on their numbers dwindled into almost non-existence. To help remedy this and jumpstart the catfish population, the GA-DNR stocked Channel Catfish into the lake and that initial stocking has had outstanding success with the population rebounding. This success continues to show in the population today, with catch rates remaining high and an abundance of Channel Catfish in the 1 – 3 pound range available to be harvested from the lake.

You can't beat chicken liver and nightcrawlers for catfish bait. The highest concentrations of Channel Catfish are usually on the Chattooga River arm within eye-shot of the boat ramp.

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Additional Information

Lake Tugalo 2023 Angler Card

Lake Tugalo has a 25 hp motor restriction, which makes this lake an excellent destination for those who fish from kayaks or small boats. Because of Lake Tugalo's rugged access roads, anglers should use vehicles with four-wheel drive and trailer small boats less than 16-feet long. Boating access at the

Stone Place Boat Ramp on the Georgia side of the lake is available through Tallulah Gorge State Park, which is located off Hwy. 441 in Tallulah Falls, Ga. Less rugged access to the lake is available at the South Carolina Boat Ramp located on Bull Sluice Road. Directions to the

South Carolina Boat Ramp are as follows: From Hwy. 441 in Clayton, Ga., turn east onto Hwy. 76. After crossing the Chattooga River Bridge into South Carolina, travel about three miles and turn right onto Orchard Road. At the stop sign, turn right onto Battle Creek Road. At the fork in the road, bear right. After passing Damascus Church, turn right onto the gravel road. This long, winding gravel road will lead to the boat ramp, which becomes paved and very steep as you approach the parking area.

A walleye fishing guidebook is available at no cost on the Wildlife Resources Division website and can be downloaded by clicking here.

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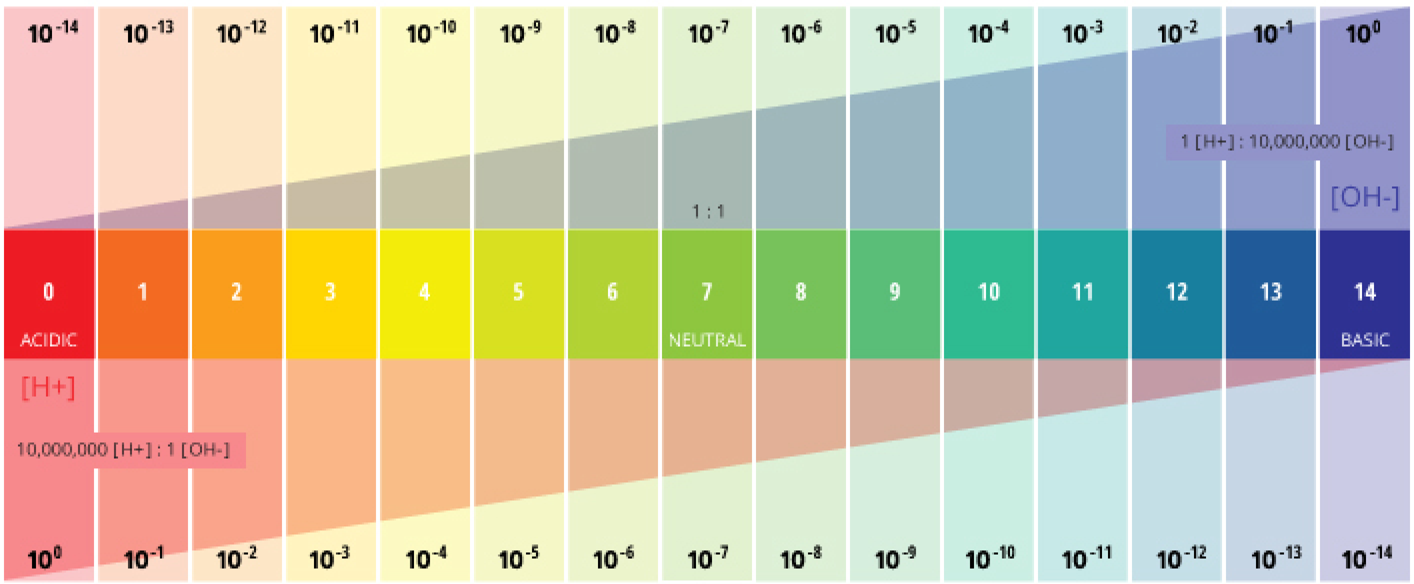
pH of Water

What is pH?

pH is a determined value based on a defined scale, similar to temperature. This means that pH of water is not a physical parameter that can be measured as a concentration or in a quantity. Instead, it is a figure between 0 and 14 defining how acidic or basic a body of water is along a logarithmic scale [1]. The lower the number, the more acidic the water is. The higher the number, the more basic it is. A pH of 7 is considered neutral. The logarithmic scale means that each number below 7 is 10 times more acidic than the previous number when counting down. Likewise, when counting up above 7, each number is 10 times more basic than the previous number [2].



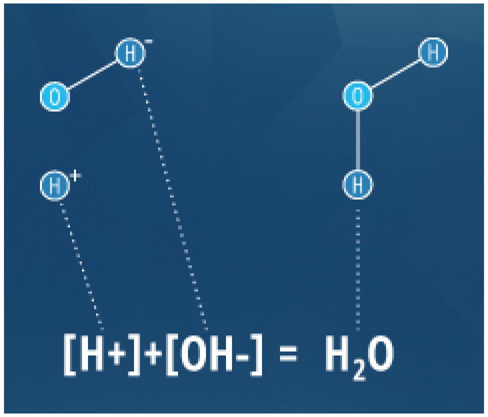
The logarithmic scale of pH means that as pH increases, the H+ concentration will decrease by a power of 10. Thus at a pH of 0, H+ has a concentration of 1 M. At a pH of 7, this decreases to 0.0000001 M. At a pH of 14, there is only 0.00000000000001 M H+.

pH stands for the "power of hydrogen" [3]. The numerical value of pH is determined by the molar concentration of hydrogen ions (H+) [3]. This is done by taking the negative logarithm of the H+ concentration (-log(H+)). For example, if a solution has a H+ concentration of 10^{-3} M, the pH of the solution will be $-\log(10^{-3})$, which equals 3.

This determination is due to the effect of hydrogen ions (H+) and hydroxyl ions (OH-) on pH. The higher the H+ concentration, the lower the pH, and the higher the OH- concentration, the higher the pH. At a neutral pH of 7 (pure water), the concentration of both H+ ions and OH- ions is 10^{-7} M. Thus the ions H+ and OH- are always paired – as the concentration of one increases, the other will decrease; regardless of pH, the sum of the ions will always equal 10^{-14} M [2]. Due to this influence, H+ and OH- are related to the basic definitions of acids and bases.

Acids and Bases

As an operational definition, an acid is a substance that will decrease pH when added to pure water. In the same manner, a base is a substance that will increase the pH of water [4]. To further define these substances, Arrhenius determined in 1884 that an acid will release a hydrogen ion (H+) as it dissolves in water, and a base will release a hydroxyl ion (OH-) in water [4]. However, there are some substances that fit the operational definition (altering pH), without fitting the Arrhenius definition (releasing an ion). To account for this, Bronsted and Lowry redefined acids and bases; an acid releases a hydrogen ion or proton (equivalent to H+) and a base accepts a hydrogen ion or proton [4]. This means that acids and bases can cancel each other out, as shown in the water equation to the right.



Acid-base pairs can neutralize each other like H+ and OH- do in this equation.

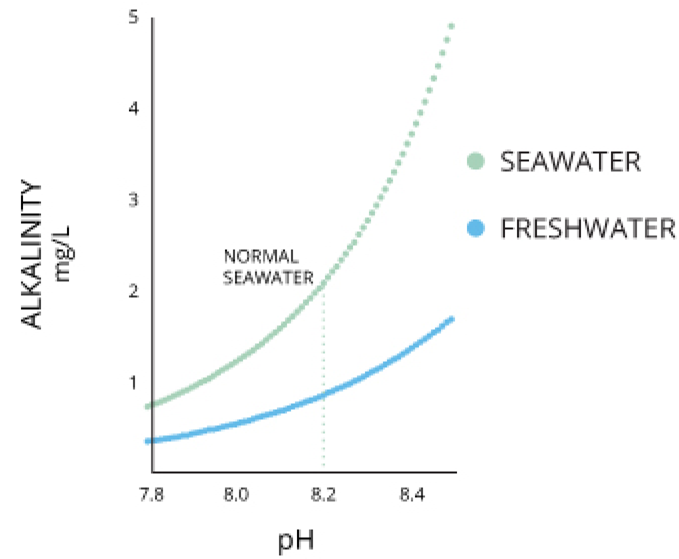
Basic or Alkaline

The terms "alkaline" and "basic" mean approximately the same thing. By the Bronsted-Lowry definition, basic describes any substance that reduces the hydrogen ion concentration and increases the pH of water, or in other words, a base [4]. Alkaline comes from alkali, which refers to ionic compounds (salts) containing alkali metal or alkaline earth metal elements that form hydroxide ions when dissolved in water [5]. Alkali salts are very common and dissolve easily. Due to the hydroxide ions they produce (which increase pH), all alkalis are bases. Some sources define any soluble base as an alkali [5]. As such, soluble bases can be described as "basic" or "alkaline". However, insoluble bases (such as copper oxide) should only be described as basic, not alkaline.

Common examples of alkalis include milk of magnesia – Mg(OH)2, caustic potash – KOH, slaked lime/limewater – Ca(OH)2, and caustic soda (lye) – NaOH.

Alkalinity and the pH of Water

Alkalinity does not refer to alkalis as alkaline does [6]. While alkalinity and pH are closely related, there are distinct differences. The alkalinity of water or a solution is the quantitative capacity of that solution to buffer or neutralize an acid. In other words, alkalinity is a measurement of water's ability to resist changes in pH. This term is used interchangeably with acid-neutralizing capacity (ANC) [7]. If a body of water has a high alkalinity, it can limit pH changes due to acid rain, pollution or other factors [8]. The alkalinity of a stream or other body of water is increased by carbonate-rich soils (carbonates and bicarbonates) such as limestone, and decreased by sewage outflow and aerobic respiration. Due to the presence of carbonates, alkalinity is more closely related to hardness than to pH (though there are still distinct differences). However, changes in pH can also affect alkalinity levels (as pH lowers, the buffering capacity of water lowers as well) [6]. pH and alkalinity are directly related when water is at 100% air saturation [9].

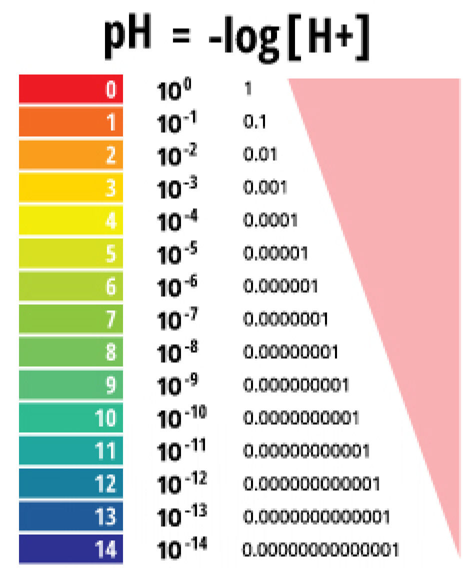


Alkalinity and pH are directly related at 100% air saturation.

The alkalinity of water also plays an important role in daily pH levels. The process of photosynthesis by algae and plants uses hydrogen, thus increasing pH levels [10]. Likewise, respiration and decomposition can lower pH levels. Most bodies of water are able to buffer these changes due to their alkalinity, so small or localized fluctuations are quickly modified and may be difficult to detect [10].

pH and Alkalinity Units

pH values are reported as a number between 0 and 14 as a standard pH unit. This unit is equivalent to the negative logarithm of the hydrogen ion molar concentration (-log(H+)) in the solution. Depending on the accuracy of the measurement, the pH value can be carried out to one or two decimal places.



However, because the pH scale is logarithmic, attempting to average two pH values would be mathematically incorrect. If an average value is required, it can be reported as a median or a range, not as a simple calculation [10].

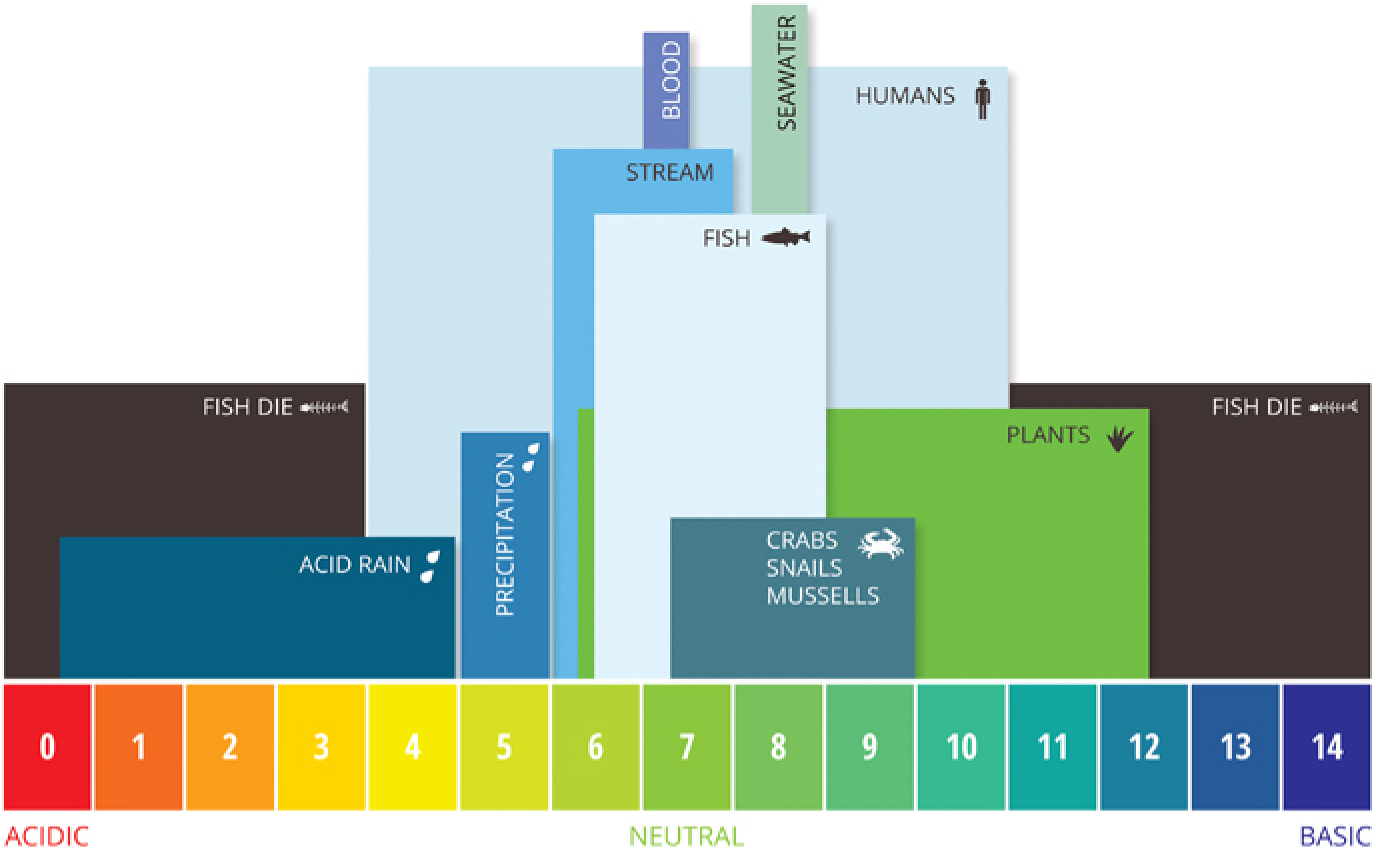
Alkalinity can be reported as mg/L or microequivalents per liter (meq/L). When in mg/L, it refers to carbonate ($CO3^{2-}$), bicarbonate ($HCO3^{-}$) or calcium carbonate ($CaCO3$) concentrations, though calcium carbonate is most common [11].

1 mg/L alkalinity as $CaCO3$ = 0.01998 meg/L alkalinity
1 mg/L alkalinity as $CaCO3$ = 0.5995 mg/L alkalinity as $CO3^{2-}$
1 mg/L alkalinity as $CaCO3$ = 1.2192 mg/L alkalinity as $HCO3^{-}$

pH values are determined on a logarithmic scale.

Why is pH Important?

If the pH of water is too high or too low, the aquatic organisms living within it will die. pH can also affect the solubility and toxicity of chemicals and heavy metals in the water [12]. The majority of aquatic creatures prefer a pH range of 6.5-9.0, though some can live in water with pH levels outside of this range.

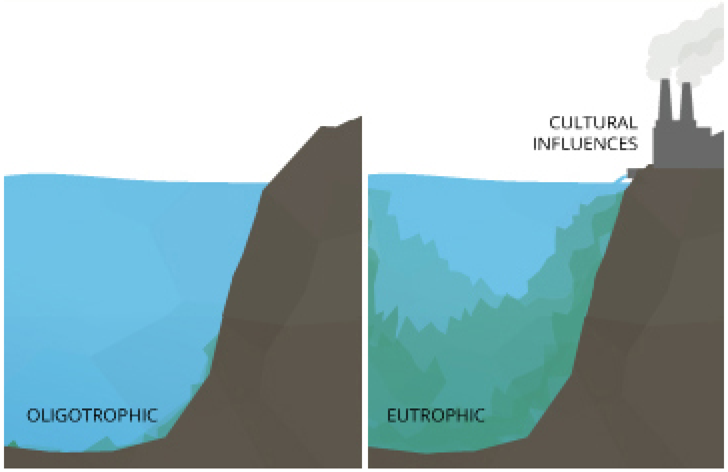


Aquatic pH levels. The optimum pH levels for fish are from 6.5 to 9.0. Outside of optimum ranges, organisms can become stressed or die.

As pH levels move away from this range (up or down) it can stress animal systems and reduce hatching and survival rates. The further outside of the optimum pH range a value is, the higher the mortality rates. The more sensitive a species, the more affected it is by changes in pH. In addition to biological effects, extreme pH levels usually increase the solubility of elements and compounds, making toxic chemicals more “mobile” and increasing the risk of absorption by aquatic life [13].

Aquatic species are not the only ones affected by pH. While humans have a higher tolerance for pH levels (drinkable levels range from 4-11 with minimal gastrointestinal irritation), there are still concerns [14]. pH values greater than 11 can cause skin and eye irritations, as does a pH below 4. A pH value below 2.5 will cause irreversible damage to skin and organ linings [14]. Lower pH levels increase the risk of mobilized toxic metals that can be absorbed, even by humans, and levels above 8.0 cannot be effectively disinfected with chlorine, causing other indirect risks [14]. In addition, pH levels outside of 6.5-9.5 can damage and corrode pipes and other systems, further increasing heavy metal toxicity.

Even minor pH changes can have long-term effects. A slight change in the pH of water can increase the solubility of phosphorus and other nutrients – making them more accessible for plant growth [10]. In an oligotrophic lake, or a lake low in plant nutrients and high in dissolved oxygen levels, this can cause a chain reaction. With more accessible nutrients, aquatic plants and algae thrive, increasing the demand for dissolved oxygen. This creates a eutrophic lake, rich in nutrients and plant life but low in dissolved oxygen concentrations. In a eutrophic lake, other organisms living in the water will become stressed, even if pH levels remained within the optimum range.



A minor increase in pH levels can cause a oligotrophic (rich in dissolved oxygen) lake to become eutrophic (lacking dissolved oxygen).

Factors that Influence the pH of Water

There are many factors that can affect pH in water, both natural and man-made. Most natural changes occur due to interactions with surrounding rock (particularly carbonate forms) and other materials. pH can also fluctuate with precipitation (especially acid rain) and wastewater or mining discharges [13]. In addition, CO2 concentrations can influence pH levels.

Carbon Dioxide and pH

Carbon dioxide is the most common cause of acidity in water [15]. Photosynthesis, respiration and decomposition all contribute to pH fluctuations due to their influences on CO2 levels. The extremity of these changes depends on the alkalinity of the water, but there are often noticeable diurnal (daily) variations [16]. This influence is more measurable in bodies of water with high rates of respiration and decomposition.

While carbon dioxide exists in water in a dissolved state (like oxygen), it can also react with water to form carbonic acid:

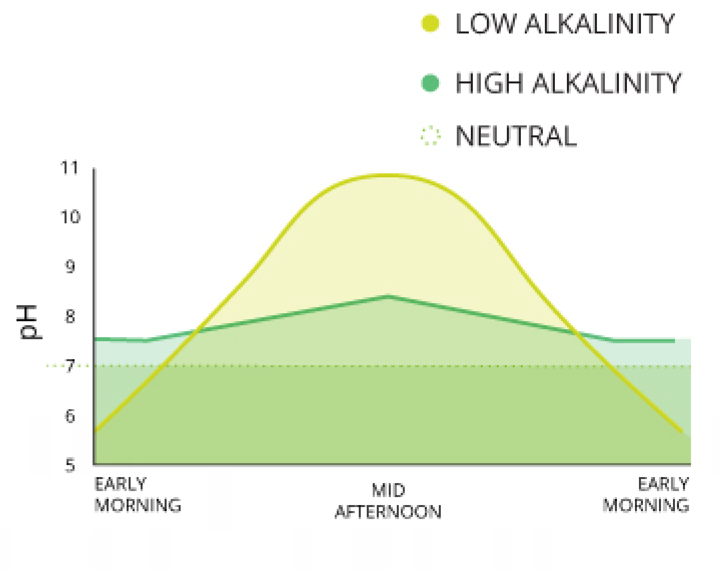
$CO_2 + H_2O \Leftrightarrow H_2CO_3$

H_2CO_3 can then lose one or both of its hydrogen ions:

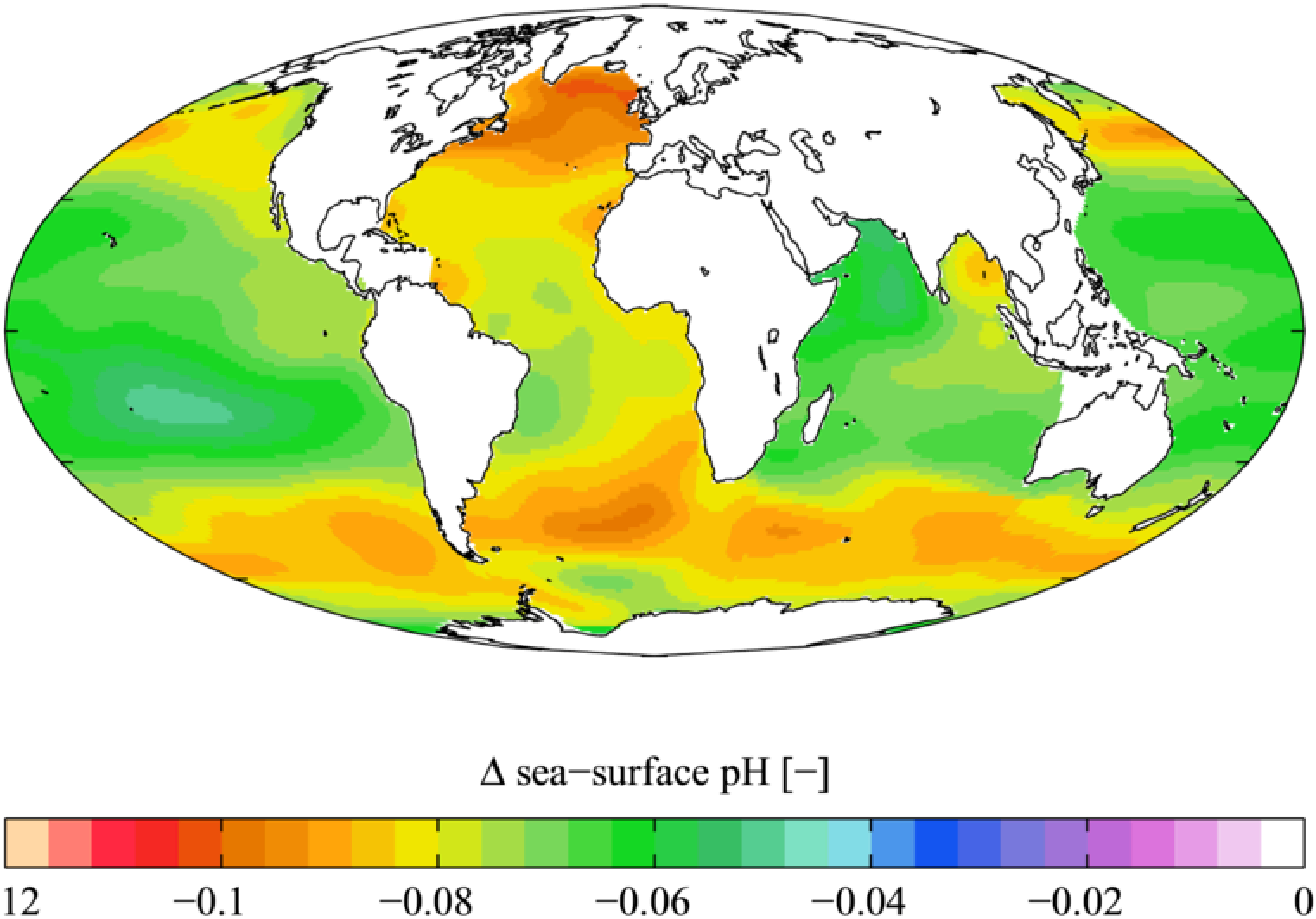
$H_2CO_3 \Leftrightarrow HCO_3^- + H^+$ …. $HCO_3^- \Leftrightarrow CO_3^{2-} + H^+$

The released hydrogen ions decrease the pH of water[15]. However, this equation can operate in both directions depending on the current pH level, working as its own buffering system. At a higher pH, this bicarbonate system will shift to the left, and CO_3^{2-} will pick up a free hydrogen ion.

This reaction is usually minimal as H_2CO_3 has a low solubility constant (Henry's Law) [15]. However, as CO_2 levels increase around the world, the amount of dissolved CO_2 also increases, and the equation will be carried out from left to right. This increases H_2CO_3, which decreases pH. The effect is becoming more evident in oceanic pH studies over time.



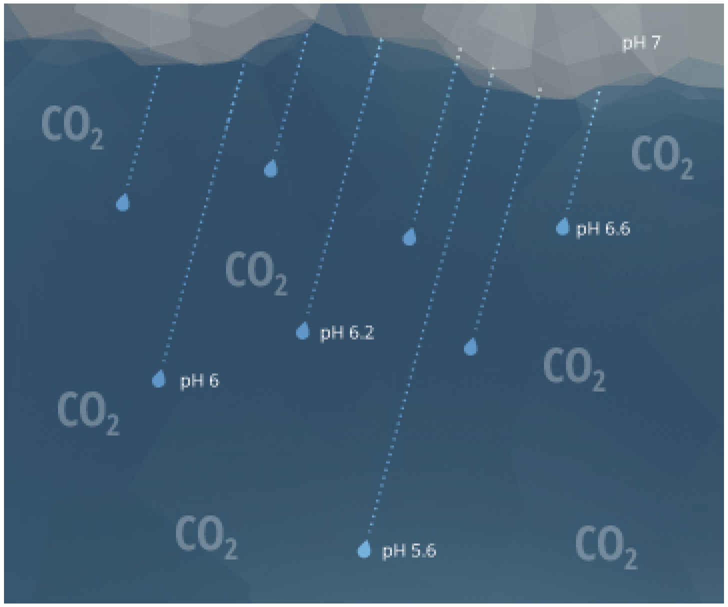
pH levels can fluctuate daily due to photosynthesis and respiration in the water. The degree of change depends on the alkalinity of the water.



Total change in annual oceanic pH levels from 1700s to 1990s. (data: World Ocean Atlas 2009; photo credit: Plumbago; Wikipedia Commons)

The above equations also explain why rain has a pH of approximately 5.65 [15]. As raindrops fall through the air, they interact with carbon dioxide molecules in the atmosphere. This creates H2CO3 in the raindrops, lowering the rain's pH value [17]. A pH level of 5.65, though acidic, is not considered acid rain. Natural, unpolluted rain or snow is expected to have pH levels near 5.6, assuming a standard atmospheric CO2 concentration of 0.0355% [15]. Acid rain requires a pH below 5.0 [21].

5.65 is also the pH of water that has equilibrated with the air and has not come in contact with carbonate materials or limestone.



Carbon dioxide in the atmosphere decreases the pH of precipitation.

Natural pH Influences

Carbonate materials and limestone are two elements that can buffer pH changes in water. Calcium carbonate (CaCO3) and other bicarbonates can combine with both hydrogen or hydroxyl ions to neutralize pH[18]. When carbonate minerals are present in the soil, the buffering capacity (alkalinity) of water is increased, keeping the pH of water close to neutral even when acids or bases are added. Additional carbonate materials beyond this can make neutral water slightly basic.

Limestone quarries have higher pH levels due to the carbonate materials in the stone.

As mentioned earlier, unpolluted rain is slightly acidic (pH of 5.6). The pH of rain can also be lowered due to volcanic ash, sulfate-reducing bacteria in wetlands, airborne particulates from wildfires and even lightning [19]. If rain falls on a poorly buffered water source, it can decrease the pH of nearby water through runoff.

Lightning can lower the pH of rain.

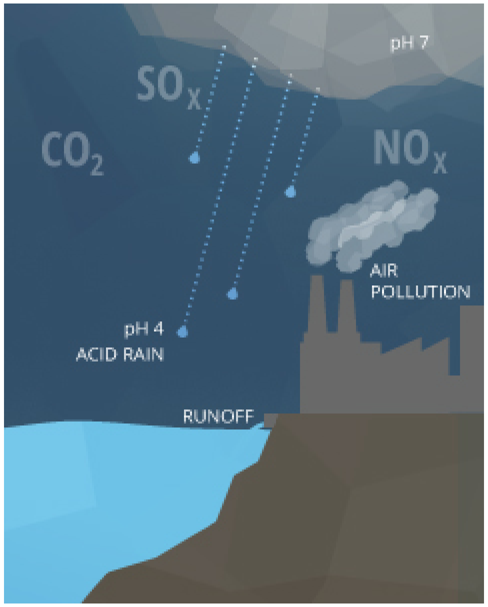
Decomposing pine needles can decrease pH.

Pine or fir needles can also decrease the pH of soil, and any water that runs over it, as they decompose [18]. Intense photosynthesis increases the pH of water as it removes CO2, though this change is usually diurnal [20].

Man-Made pH Influencers

Anthropogenic causes of pH fluctuations are usually related to pollution. Acid rain is one of the best known examples of human influence on the pH of water. Any form of precipitation with a pH level less than 5.0 is known as acid rain [21]. This precipitation comes from the reaction of water with nitrogen oxides, sulfur oxides and other acidic compounds, lowering its already slightly acidic pH. These emissions usually come from mining and smelting operations or fossil fuel combustion (coal burning and automobiles) [18]. Extremely high levels of CO2 can also further decrease the pH of rain [17].

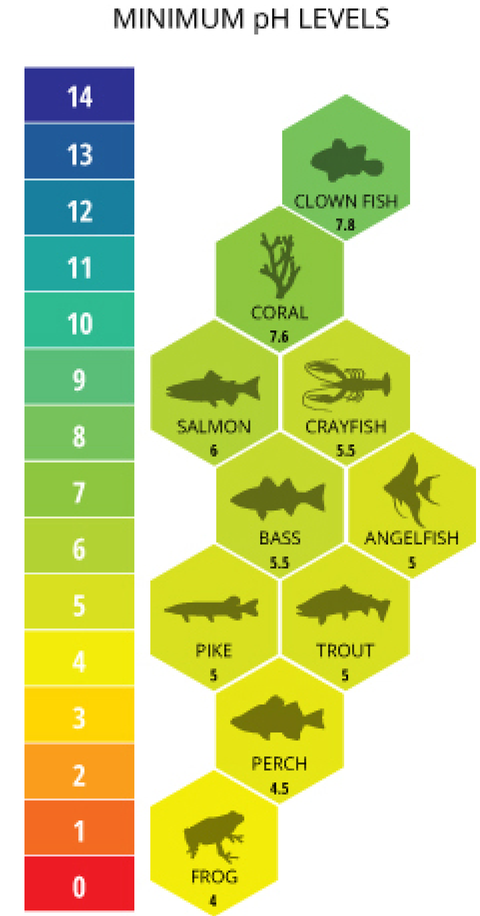
Point source pollution is a common cause that can increase or decrease pH depending on the chemicals involved [18]. These chemicals can come from agricultural runoff, wastewater discharge or industrial runoff. Mining operations (particularly coal) produce acid runoff and acidic groundwater seepage if the surrounding soil is poorly buffered [22]. Wastewater discharge that contains detergents and soap-based products can cause a water source to become too basic.



Pollution in the air, soil or directly in the water can all affect pH.

Typical pH Levels

Typical pH levels vary due to environmental influences, particularly alkalinity. The alkalinity of water varies due to the presence of dissolved salts and carbonates, as well as the mineral composition of the surrounding soil. In general, the higher the alkalinity, the higher the pH; the lower the alkalinity, the lower the pH [6]. The recommended pH range for most fish is between 6.0 and 9.0 with a minimum alkalinity of 20 mg/L, with ideal $CaCO_3$ levels between 75 and 200 mg/L [20].



Recommended minimum pH levels for aquatic life.

Oceanic organisms like clownfish and coral require higher pH levels. pH levels below 7.6 will cause coral reefs to begin to collapse do to the lack of calcium carbonate [39]. Sensitive freshwater species such as salmon prefer pH levels between 7.0 and 8.0, becoming severely distressed and suffering physiological damage due to absorbed metals at levels below 6.0 [40].

Environmental Considerations

Natural precipitation, both rain and snow, has a pH near 5.6 due to contact with CO_2 and other atmospheric influences. Most grasses and legumes prefer soils with a pH of 4.5-7.0, so the slight acidity of rain can benefit carbonate soils [23].

The acidity of the surrounding environment can also affect the pH of water. This is most obvious near mining areas, but the effect can also occur naturally. Acid runoff depletes the water's alkalinity and lowers pH below optimum levels. This may be tolerable for some aquatic species (such as frogs) but not for most fish. Some frogs and other amphibians can often tolerate pH levels as low as 4.0 [24]. Acidic soils in the Amazon cause many of the lakes and rivers to naturally have low pH values [38]. Due to the dissolved humic substances from runoff and uptake, "blackwater" sources can have a pH as low as 4.43. "Clearwater" sources will have a slightly higher, but still acidic, pH value [38]. That is why angel fish and discus from the Amazon River Basin can thrive quite happily in waters with a pH as low as 5.0 [25].

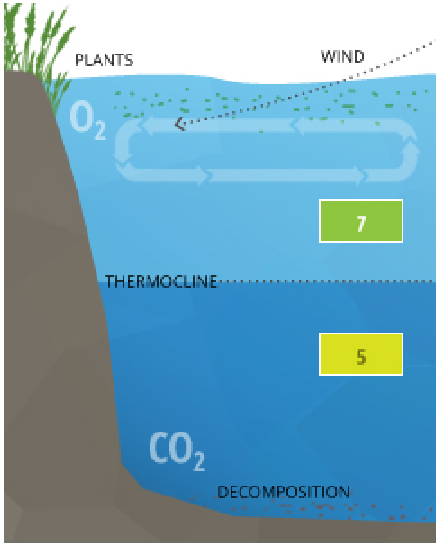
Seawater has a pH around 8.2, though this can range between 7.5 to 8.5 depending on its local salinity. pH levels will increase with salinity until the water reaches calcium carbonate ($CaCO_3$) saturation [16]. The oceans generally have a higher alkalinity due to carbonate content and thus have a greater ability to buffer free hydrogen ions [27].

Freshwater lakes, ponds and streams usually have a pH of 6-8 depending on the surrounding soil and bedrock [21]. In deeper lakes where stratification (layering) occurs, the pH of water is generally higher (7.5-8.5) near the surface and lower (6.5-7.5) at greater depths [10]. Some states, such as Alaska, are attempting to maintain a pH standard for water quality. The Alaska Water Quality Standard requires pH levels between 6.5 and 8.5 to protect the many salmon populations in the state [40].

Stratification Considerations

Stratification is usually caused by temperature differences within a body of water, where each layer of water does not mix with the layers above or below [37]. These layers are separated by clines, known as thermoclines (temperature divides) or chemoclines (chemistry gradients). Chemoclines can be based on oxygen, salinity, or other chemical factors that do not cross the cline, such as carbon dioxide. Due to CO_2's influence on the pH of water, stratification can cause pH levels to differ across a cline.

Differences in pH levels between water strata are due to increased CO_2 from respiration and decomposition below the thermocline. In crater lakes such as Lake Nyos or Lake Monoun, the pH rapidly drops from a surface level around 7 to 5.5 below 60 m (at the thermocline and chemocline) [26]. This significant drop comes from the saturated CO2 that is stored up in the lower strata of the lake.



Stratification can cause pH levels within a body of water to differ above and below the cline.

Adaptability

While ideal pH levels for fish are 7-8 (fish blood has a pH of 7.4) [20], most fish can adapt to the pH level of their environment (6.0-9.0) as long as there are no dramatic fluctuations. A dramatic fluctuation is considered a shift in pH of 1.4 (up or down) [22]. For saltwater fish, the pH of water should remain between 7.5 and 8.5 [9].

Unusual pH Levels and Consequences

Harmful effects become noticeable when the pH of water falls below 5.0 or rise above 9.6. Ill effects due to acidification are more pronounced in saltwater fish due to their adaptation to a higher pH. When pH is below optimal levels, fish become susceptible to fungal infections and other physical damage [16]. As the pH of water falls, the solubility of calcium carbonate is reduced, inhibiting shell growth in aquatic organisms [16]. In general, fish reproduction is affected at pH levels below 5.0 and many species (such as saltwater fish or sensitive freshwater fish like smallmouth bass) will leave the area [21]. Fish begin to die when pH falls below 4.0 [12].

Low pH levels can encourage the solubility of heavy metals [12]. As the level of hydrogen ions increases, metal cations such as aluminum, lead, copper and cadmium are released into the water instead of being absorbed into the sediment. As the concentrations of heavy metals increase, their toxicity also increases. Aluminum can limit growth and reproduction while increasing mortality rates at concentrations as low as 0.1-0.3 mg/L [22]. In addition, mobilized metals can be taken in by organisms during respiration, causing physiological damage [22] . This is particularly detrimental to species such as rainbow trout [13].

On the other side of the spectrum, high pH levels can damage gills and skin of aquatic organisms and cause death at levels over 10.0. While some african cichlids thrive at high pH levels (up to 9.5), most fish cannot tolerate them. Death can occur even at typical levels (9.0) if ammonia is present in the water [21]. At low and neutral pH levels, ammonia combines with water to produce an ammonium ion:

Stony corals begin to bleach and deteriorate as carbonate and pH levels fall.

$NH_3 + H_2O \Leftrightarrow NH_4^+ + OH^-$

Ammonium, NH_4^+, is non-toxic and will not affect aquatic life. However, at pH levels over 9, the equation reverses and ammonia is released into the water [22]. Ammonia, NH_3, is extremely toxic to aquatic organisms, and as pH increases, the mortality rates rise with the NH_3 concentration.

On the ecosystem side, mosses can begin invading a body of water as the pH of water falls below 5. In eutrophic lakes, pH-tolerant algae can dominate, driving the pH levels to diurnal high and low extremes, forming algae blooms that can kill the lake [16].

Low pH-tolerant algae can form blooms that can kill the lake.

Alkaline and Acid Lakes

Spread across the world are a number of lakes with unusual pH levels. Alkaline lakes, also known as soda lakes, generally have a pH level between 9 and 12. This is often due to a high salt content (though not every salt lake has a high pH). These lakes have high concentrations of minerals, particularly dissolved salts: sodium, calcium, magnesium carbonates and bicarbonates [28]. Depending on the lake, borates, sulfates and other elements (usually strong base ions) can also be present [29]. Alkaline lakes are formed when the only outlet for water is evaporation, leaving the minerals behind to accumulate [30]. These minerals often form columns of mineral deposits, known as tufa columns. Many alkaline lakes are a commercial resource for soda ash and potash, while others are popular tourist destinations for their “magical” healing properties (due to the mineral content).

Soap Lake in Washington is an alkaline lake assumed to have healing properties (Photo Credit: Steven Pavlov via Wikipedia Commons)

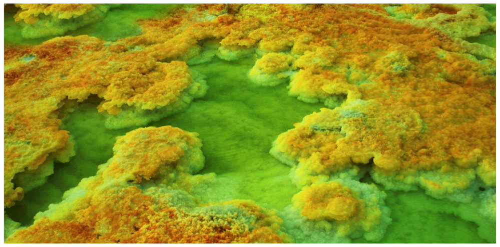
A notorious example of an alkaline lake is Lake Natron in Tanzania. Lake Natron has a pH up to 10.5 due to high concentrations of sodium carbonate decahydrate (soda ash) and sodium bicarbonate (baking soda) that enters the water from the surrounding soil [31]. While the lake supports a thriving ecosystem, including flamingos, alkaline tilapia and pH-resistant algae, Nick Brant, a photographer, has created many haunting images of animals that died in this lake [31]. The bodies of these animals are preserved by the sodium carbonate, much like the ancient Egyptian mummification process.

A calcified flamingo preserved by the soda minerals in Lake Natron. (Photo Credit: © Nick Brandt, 2013 Courtesy of Hasted Kraeutler Gallery, NY.)

Acid lakes usually develop near volcanoes, where sulfuric acid, hydrogen sulfide, hydrofluoric acid, hydrochloric acid and carbon dioxide can leach into the water [32]. In non-volcanic areas, acid lakes can also develop after acidic deposition from events such as acid rain, pollution or acid runoff from mining operations [33]. Much like their alkaline counterparts, acid lakes have no outlet except evaporation, concentrating the sulfates and acids. The acids can enter the water through atmospheric diffusion from coal burning, acid rain or after an eruption. In volcanic lakes, acids can enter the water through an active fumarole, or volcanic vent.

The acid lakes at Dallol in Ethiopia are the result of acid leaching from nearby volcanoes. The sulfur and iron in the water leave yellow and rust-colored deposits around the water's edge.

With a pH level below 5.0, few organisms can live in acid lakes. However, there is one notable exception: the Osorezan dace, or Japanese dace. This fish thrives in the acidic waters of Lake Osorezan, resting comfortably at a pH of 3.5, and swims into neutral pH waters only to spawn [34].



Sulfur and iron deposits at one of Dallol's acid lakes.

Ocean Acidification

Ocean acidification is caused by an influx of dissolved carbon dioxide. As atmospheric CO2 levels increase due to anthropogenic causes, dissolved CO2 also increases, which in turn decreases the pH of water.

When water becomes saturated with CO2, it not only reduces the ocean's pH, but depletes the calcium carbonate sources as well [35]. Calcium carbonate, CaCO3, is a necessary ingredient in building corals, shells and exoskeletons for many aquatic creatures. As $CO3^{2-}$ levels decrease, it becomes more difficult for marine creatures to build their shells.

As mentioned in the section "Carbon Dioxide and pH", additional CO2 increases the number of hydrogen ions in the water, reducing pH:

$CO2 + H2O \Leftrightarrow H2CO3 \ldots H2CO3 \Leftrightarrow (H+) + HCO3^{-}$

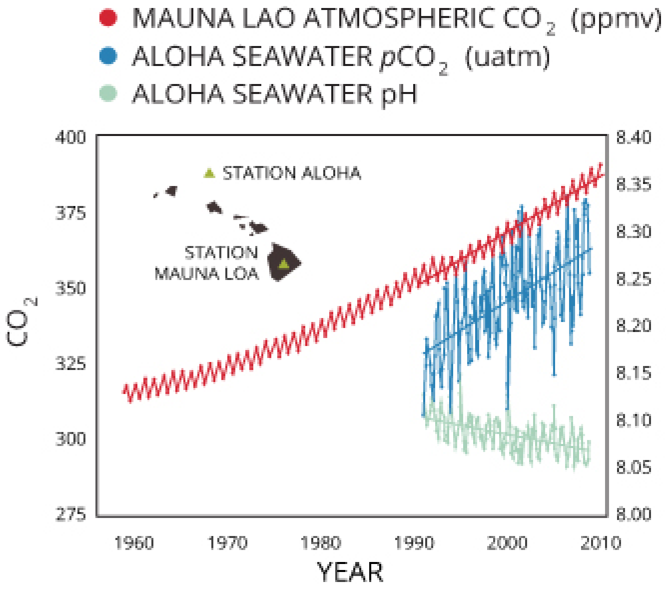
At pH levels between 6.4 and 10.33, some of those hydrogen ions attach to carbonate ions [22]:

$(H+) + CO3^{2-} \Leftrightarrow HCO3^{-}$

Thus as CO2 levels increase, the availability of carbonate, $CO3^{2-}$ decreases, reducing the amount available for shell and coral building [36].

$CO2 + H2O + CO3^{2-} \Leftrightarrow 2HCO3^{-}$

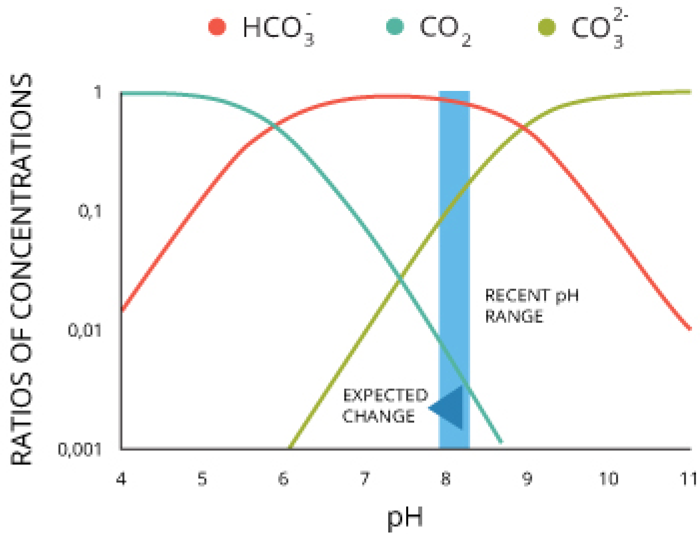
High CO2 levels also make it more difficult to maintain current shells due to lower pH levels and competition for carbonate [35].



As atmospheric CO2 increases, dissolved CO2 will increase and the pH of water will decrease. (data: NOAA/ESRL and University of Hawaii; credit: SERC EarthLabs)

Furthermore, the air saturation of water is based on partial pressures from Henry's law. As CO2 levels in the air increase, so too does their partial pressure. This reduces the partial pressure of oxygen, reducing its saturation levels and contributing to hypoxic (low O2) conditions [35].

While the oceans will never become "acidic" (with a pH of less than 7), even decreasing pH a slight amount stresses saltwater organisms and increases mortality rates. pH is logarithmic, meaning that a decrease by 0.1 is equivalent to nearly a 30% increase in acidity [35].



At an oceanic pH of 8.3, carbonate levels are high enough for coral building. As CO2 increases and pH decreases, carbonate levels will quickly drop below optimum levels.

Cite This Work

Fondriest Environmental, Inc. “pH of Water.” Fundamentals of Environmental Measurements. 19 Nov. 2013. Web. < https://www.fondriest.com/environmental-measurements/parameters/water-quality/ph/ >.

More Information

- pH Measurement Methods
- pH Meters
- pH Sensors
- Applications
- References