Data and Model Integration to Assess Harmful Algal Blooms in Smith Mountain Lake, Virginia

Final Report

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Project Goal

The goal of this study is for the Virginia Department of Environmental Quality (DEQ), Virginia Water Resources Research Center (VWRRC) at Virginia Polytechnic Institute and State University (Virginia Tech), and Smith Mountain Lake Association (SMLA) to work in partnership to address the request made by the General Assembly in 2024 by way of HB30 Budget Bill. The bill charges DEQ with the following:

> *M. Out of the amounts in this item, $150,000 the first year from the general fund is provided for the department, in collaboration with Virginia Polytechnic and State University and the Smith Mountain Lake Association, to conduct a study of the harmful algal blooms occurring at Smith Mountain Lake. The research shall include evaluation of conditions that have led to the appearance of harmful algal blooms and include recommendations for prevention of further occurrences.*

Project Objectives

The partnership, comprised of DEQ, SMLA, and VWRRC at Virginia Tech, identified the following objectives for the project:

- Objective 1: Verify whether HABs are recurring in SML and, if so, the spatial and temporal extent of HABs in the lake;
- Objective 2: Identify the major factors and conditions leading to the occurrence of HABs in SML; and
- Objective 3: Identify general management approaches to prevent and/or mitigate HABs by considering short-term and long-term strategies and practices.

Background

Smith Mountain Lake

Smith Mountain Lake (SML) is a 22,000-acre reservoir created by impounding the Roanoke River in the 1960s for the generation of electricity. It provides a popular recreational area, well known by local anglers, wakeboarders, and boaters, and is home to a lakeside community of more than 20,000 (SML Regional Chamber of Commerce, 2025).

Smith Mountain Lake lies within the Virginia counties of Bedford, Franklin and Pittsylvania. There are two primary branches: 1) the Roanoke River arm, which includes the cities of Roanoke and Salem in its watershed, and 2) the Blackwater River arm, which is generally rural and has more agricultural land uses. Residential housing surrounds much of the lake.[1]

[1] Although technically a reservoir – meaning it was formed by damming a river instead of forming naturally as lakes do – throughout the report, we will refer to SML as a "lake."

The lake is approximately 40 miles in length and has many small coves that create over 500 miles of shoreline. The lake is characterized by deep water, with an average depth of 55 feet and depths exceeding 200 feet near the dam (Gibson and Church 2024). At full pond, the lake is 795 feet above sea level. The lowest recorded water levels for SML are approximately 7 feet below full pond, and the highest levels are approximately 5 feet above the full pond level (American Electric Power Company, Inc. [AEP], 2023). Current and archived[2] water levels for SML are presented graphically by Lipscomb (2025), and annual minimum and maximum elevations back to 1966 are available from the American Electric Power Company (AEP, 2023).

American Electric Power Company manages the SML dam and operates a pumped-storage system, where water from SML generates electricity as it flows through the dam into a lower reservoir, Leesville Lake. A 2-foot decrease in lake level for SML fills Leesville Lake. Once Leesville Lake is full, power generation at the SML dam needs to stop, and water below the SML dam is pumped back into SML. The power company manages this system so that during periods of low demand for electricity, water below the dam is pumped back into SML for reuse in generating electricity during periods of high demand (AEP, 2023).

Historically, bloom reports have been infrequent in SML and short lived. However, the Virginia Department of Health (VDH) issued the first no-swim advisory in parts of SML in 2023 due to potential harmful algal blooms (Branch, 2024). The advisory initially included the entire Blackwater arm of the lake. After a month, the advisory was lifted in the lower half of the Blackwater, but it remained in effect on the Blackwater arm upstream of Gills Creek for another seven weeks.

Harmful Algal Blooms

Blooms occur within a lake when there is a rapid and significant increase in plankton (free-floating organisms). Individually, the organisms are microscopic, but the collective bloom is visible. In a 2021 report to the General Assembly, DEQ distinguishes between an “algal bloom” and a “harmful algal bloom (HAB).” An algal bloom was defined as “the rapid growth of a species or number of species of algae.” Harmful algal blooms were defined as blooms that have “algae and cyanobacteria that produce toxins that may adversely affect human health through ingestion of contaminated water or shellfish (DEQ, 2021).”

Within SML, both algae and cyanobacteria occur naturally. Like plants, both algae and cyanobacteria are photosynthetic organisms. Algae are eukaryotic (have a cell nucleus) but lack roots, stems, and leaves. Cyanobacteria are bacteria; they are prokaryotic (lack a cell nucleus). Because of their ability to photosynthesize and the bluish-green color of many cyanobacterial blooms, cyanobacteria are often referred to as “blue-green algae,” even though they are not algae and their blooms are not always blue-green in color.

The VDH bases recreational advisories on toxins that are produced by some cyanobacteria. Not all cyanobacteria can produce toxins, and those with the ability to make toxins do not produce toxins all the time. Thus, toxins are not always present during cyanobacterial blooms. Conversely, toxin levels can become elevated in the water before a bloom is visible, and toxins

[2] Archived back to October 8, 2004

can be present in water after a bloom dissipates. The presence of cyanobacterial toxins cannot be determined without laboratory testing; therefore, it is generally advised to avoid contact with water whenever a cyanobacterial bloom is observed.

Favorable environmental conditions are needed for the formation of HABs, with the most prolonged HABs tending to occur in warm, stagnant water that is rich in nutrients (phosphorus and nitrogen) and accessible to sunlight. When environmental conditions become unfavorable, such as during winter, some cyanobacteria can go dormant (e.g., as akinetes) until favorable growing conditions return.

Role of Nutrients

Nutrients, particularly phosphorus and nitrogen, strongly control the growth potential of cyanobacteria. Cyanobacteria compete with other bacteria, algae, and other organisms for available nutrients and have adapted strategies to survive periods when nutrient levels are low. Some species of cyanobacteria can store phosphorus during periods of abundance for use later (Markou et al., 2014; Reynolds, 2006), and some can fix nitrogen from the air to compensate when nitrogen levels are low (Benayache et al., 2019; Gallon, 1992; Kumar et al., 2010).

Nutrients enter SML from external sources through surface water, groundwater, and atmospheric deposition. Some external loads come from point sources, meaning they originate from an identifiable and confined location, such as a pipe. Other external loads of nutrients enter SML from diffuse non-point sources; they come from many different locations, such as in agriculture and urban runoff.

Nutrients can also come from internal sources within lake systems. Under certain environmental conditions, nutrients from particulates in the water column and sediments on the lake floor can dissolve and be released back into the water. For example, low-oxygen levels (hypoxia) in the lower layer of a stratified lake can lead to phosphorus release from sediments. Many cyanobacteria species (in the genera *Aphanizomenon*, *Cylindrospermopsis*, *Dolichospermum*, *Microcystis*, *Planktothrix*, etc.) can control their position within the water column, moving to the surface during the day to photosynthesize and sinking to the bottom layers, where nutrient levels are higher, at night (Benayache et al., 2019).

Recreational Swimming Advisories

The VDH bases recreational swimming advisories on measurable toxin thresholds associated with cyanobacteria. The VDH follows its *Guidance for Cyanobacteria Bloom Recreational Advisory Management* (2025) to recommend advisories to waterbody managers when concentrations of one or more cyanotoxins are equal to or greater than the associated thresholds in Table 1.

Table 1. 2025 VDH cyanotoxin advisory criteria: Cyanobacteria bloom recreational advisory thresholds using cyanotoxin concentrations.

Metric	Concentration
microcystins	≥8 µg/L
cylindrospermopsin	≥15 µg/L
anatoxin-*a*	≥8 µg/L
saxitoxin	≥4 µg/L

Advisories are typically lifted when two consecutive sample events, at least ten days apart, indicate toxin concentrations are below advisory thresholds. In certain situations, VDH may lift advisories based on one acceptable result or may extend advisories when toxin concentrations are at or below thresholds. Additionally, advisories may be lifted in November (after the swim season has ended) even if sample results indicate thresholds are exceeded.

Prior to May 22, 2025, the guidance used by VDH specified thresholds for both cell counts of potentially toxin-producing taxa (PTOX) of cyanobacteria and toxin concentrations. Advisories were recommended when any concentration of PTOX taxa or toxin equaled or exceeded the respective threshold listed in Table 2. Recreational advisories were typically lifted when two consecutive sample events, taking place at least ten days apart, indicated all listed taxa densities and toxin concentrations were below the advisory thresholds.

Table 2. 2021 VDH hybrid advisory approach: Cyanobacteria bloom recreational advisory thresholds using cell densities and toxin concentrations for targeted cyanotoxins.

Metric	Concentration
Microcystis species	≥40,000 (total cells/mL)**
total potentially toxigenic (PTOX) cyanobacteria taxa*	≥100,000 (total cells/mL)
microcystin toxin	≥8 µg/L
cylindrospermopsin toxin	≥15 µg/L
anatoxin-*a* toxin	≥8 µg/L
saxitoxin toxin	≥4 µg/L

*PTOX taxa list was subject to change based on research. The 2024 list is included in Appendix A.
**Total PTOX cyanobacteria taxa include *Microcystis* concentrations.

The 2025 VDH guidance removes the cell density criteria and keeps the toxin criteria based on additional toxin analyses and data evaluations. Had the current guidance been in effect in 2023, SML would not have been under a recreational advisory. The 2023 advisory for SML was based on elevated cell counts of potential toxin-producing species (≥100,000 total cells/mL). Although there were no measured exceedances of toxin thresholds from the SML water samples, toxins were detected in multiple water samples, including microcystin and anatoxin-*a* concentrations exceeding 1 µg/L. In 2023, there were four reports from the public of symptoms consistent with the effects of such toxins after swimming in SML, although HAB toxicity was not confirmed. At least one person sought medical attention for their symptoms.

TMDL Studies and Implementation Plans in the SML Watershed

Here, we provide a summary of total maximum daily load (TMDL) studies and associated implementation plans for the SML watershed as they relate to water quality and nutrients (and thus cyanobacterial blooms) more specifically. Since 2001, there have been 13 TMDL studies approved by the U.S. Environmental Protection Agency (EPA) and the State Water Control Board (SWCB) within the SML watershed, six in the Roanoke watershed and seven in the Blackwater watershed (Table 3). Designated-use impairments within the SML watershed include aquatic life, contact recreation, and edible and marketable natural resources. There is also an aquatic life use impairment in the Roanoke River, Tinker Creek, and Wolf Creek for which a TMDL study is underway but has not been approved by EPA or the SWCB; proposed probable stressors for this study include sediment, nitrogen, and phosphorus, but the stressor report is not final.

A summary of the use impairments in the SML watershed and identified pollutants are in Table 4. Studies that address aquatic life impairments can identify more than one stressor (pollutant) for which reduction loads are calculated. Only one approved TMDL study concerned nutrients (phosphorus) directly. However, nine of the approved studies were for fecal coliform/*E. coli*, which are indicators of fecal contamination. Fecal matter is rich in nutrients and provides a nutrient source for cyanobacteria. Three of the approved studies were for sediments. Phosphorus is known to adsorb to sediment particles and can detach later from the sediment, contributing to nutrient pollution within waterways. Thus, all but one of the approved TMDL studies (PCBs) had an association with nutrients.

Following approval of the TMDL study by the EPA, an implementation plan (IP) is developed. The IP typically applies to an entire watershed and addresses multiple pollutants within the watershed. Two IPs have been approved by EPA and the SWCB for the Blackwater River, but the IPs on the Roanoke have only been approved by EPA (not yet approved by the SWCB; Table 5). There is also an IP under development for the Pigg River, which can influence the water quality of SML (see Pigg River draft implementation plan).

Once IPs are accepted by EPA, impacted watersheds may be eligible to receive funding for implementation of best management practices (BMPs). To demonstrate progress of accepted IPs, a progress report is created. Since approximately 20 years have passed since the Blackwater IPs were approved (in 2004 and 2006), it would be helpful to check on their progress. Stakeholders of SML are encouraged to become familiar with the IPs to gain a clear understanding of the proposed changes and BMPs. Their engagement may also be instrumental in securing funding to support execution of these practices.

Table 3. Total Maximum Daily Load (TMDL) studies conducted in the Smith Mountain Lake watershed.

TMDL Study	Use Impairment	Pollutants	EPA Approval	SWCB Approval	Hyperlinks to Documents
Roanoke River Arm of Smith Mountain Lake					
Upper Roanoke River Watershed	Aquatic Life	Sediment	05/10/2006	09/07/2006	Final Report EPA Rationale
Upper Roanoke River Watershed	Contact Recreation	*E. coli*	08/02/2006	06/27/2007	Final Report EPA Rationale
Roanoke River Watershed (Headwaters to Niagara Dam)	Edible and Marketable Natural Resources	PCBs	04/09/2010	12/09/2010	Final Report EPA Rationale
Tinker Creek Watershed	Contact Recreation	*E. coli*	08/05/2004	12/02/2004	Final Report EPA Rationale
Beaverdam Creek	Aquatic Life	Sediment	07/29/2024	11/30/2023	Final Report EPA Rationale
Beaverdam Creek	Contact Recreation	*E. coli*	07/07/2006	06/27/2007	Final Report EPA Rationale
Blackwater River Arm of Smith Mountain Lake					
Upper Blackwater River Watershed	Aquatic Life	Phosphorus; Sediment	04/26/2004	08/31/2004	Final Report EPA Rationale
Upper Blackwater River Watershed	Contact Recreation	Fecal Coliform	03/09/2001	06/17/2004	Final Report EPA Rationale
South Fork Blackwater River Watershed	Contact Recreation	Fecal Coliform	02/02/2001	06/17/2004	Final Report EPA Rationale
Middle Blackwater River Watershed	Contact Recreation	Fecal Coliform	11/30/2001	06/17/2004	Final Report EPA Rationale
Lower Blackwater River Watershed	Contact Recreation	Fecal Coliform	04/27/2001	06/17/2004	EPA Rationale
Maggodee Creek Watershed	Contact Recreation	Fecal Coliform	04/27/2001	06/17/2004	EPA Rationale
Gills Creek Watershed	Contact Recreation	Fecal Coliform	05/31/2002	06/17/2004	Final Report Modification EPA Rationale

Table 4. Use impairments and identified pollutants for which TMDLs were calculated in studies within the Roanoke and Blackwater watersheds, which feed into Smith Mountain Lake.

Use Impairment	Pollutant	Roanoke (6 TMDL Studies)	Blackwater (7 TMDL Studies)
Contact Recreation	Bacteria	3	6
Aquatic Life	Sediment	2	1
Aquatic Life	Phosphorus	--	1
Edible and Marketable Natural Resources	PCBs	1	--

Table 5. Implementation plans for the Blackwater River and Roanoke River watersheds.

IP Watershed/ Report Name	City/ County	Impairment/ Pollutant	US EPA Approval Date	SWCB Approval Date
Blackwater River	Franklin	Bacteria	2003	06/17/2004
Lower Blackwater River, Maggodee Creek, Gills Creek	Franklin	Bacteria	01/26/2006	09/27/2006
Upper Roanoke River - Part I	Bedford, Botetourt, Floyd, Franklin, Craig, Montgomery, and Roanoke counties, Roanoke City and Salem	Bacteria, Sediment	04/22/2016	
Upper Roanoke River- Part II (Technical Report, Public Report)	Bedford, Botetourt, Floyd, Montgomery, and Roanoke counties, the towns of Blacksburg and Christiansburg, and the cities of Salem and Roanoke	Bacteria, Sediment	08/18/2016	

Project Outcomes

Smith Mountain Lake Webtool

As part of addressing project objectives, we developed the SML Webtool to store and share data and analyses for the SMLA and other stakeholders. Development of the tool required a robust approach that could efficiently handle spatial data, provide interactive visualizations, and support scalable backend operations. An overview of the webtool development technologies is provided in Appendix B, and a user guide is provided in Appendix C.

The webtool can be accessed at: http://52.5.129.122/react/. Figure 1 shows the interface through which users can explore water quality data and analyses, as well as high-resolution land cover and land cover change information. The interactive map on the left allows users to explore various spatial datasets, including DEQ monitoring sites, Ferrum College tributary water quality monitoring sites, 2016 Virginia Geographic Information Network (VGIN) land cover (1 meter resolution), National Land Cover Database (NLCD) land cover change (2001–2023) (30 meter resolution), and remote sensing-derived chlorophyll index (2023) (10 meter resolution). Additional selectable layers include the boundary of SML and its two primary tributaries: the Blackwater River and the Roanoke River.

The control panel in the right corner of the map enables users to select variables for time-series visualization or variable comparisons and correlations. When a monitoring site is selected, relevant water quality variables become available in the dropdown menu.

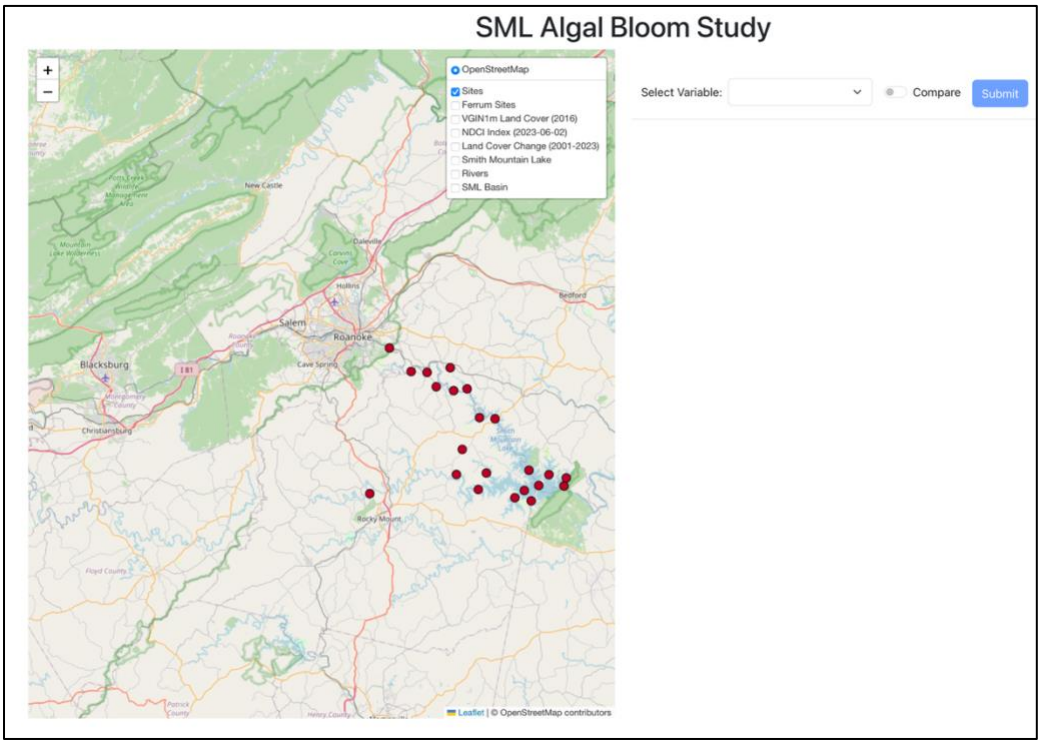

Figure 1. Interface of the SML Webtool.

Objective 1: Verify whether harmful algal blooms (HABs) are recurring in Smith Mountain Lake and, if so, the spatial and temporal extent of HABs in the lake

Meeting this objective involved gathering data related to cyanobacterial blooms (Task 1) and investigating the potential use of remotely sensed data to study blooms in SML (Task 2).

Objective 1, Task 1: In Situ Bloom Analysis

As 2023 was the first year that a HAB recreational (swimming) advisory was issued by VDH for a portion of SML, it is important to consider the future persistence and reoccurrence of HABs, and cyanobacterial blooms more generally. It will also be important to identify those areas where conditions are of most concern to target future management and monitoring efforts.

Objective 1 included a compilation of bloom reports and associated bloom-related data for SML. Historical data pertaining to public reports of potential HABs were obtained from DEQ and VDH.

Summary of Reports and Follow-up Actions

Since the 1990s, VDH has operated the HAB Hotline (888-238-6154) across Virginia, where the public can report suspected illnesses due to possible HAB exposure. The VDH also provides a HAB online report form where the public can report sightings of potential HABs. The form requests the following information: waterbody name, date and time of observation, waterbody location, county/city, contact information for person reporting observations, and comments about observations. The form also allows individuals to upload a photo that shows the condition of the water.

Following all credible reports on SML, the VDH requests that the Blue Ridge DEQ office investigate the situation and sample the water if a bloom exists. It is not possible, however, for DEQ to sample all blooms. Some blooms occur when state offices are closed. Furthermore, blooms that form offshore are often blown to other parts of the lake. Also, many blooms are short-lived and are easily broken up by wind or wave action, so can dissipate before DEQ arrives. Water samples collected prior to May 22, 2025 for HAB testing were analyzed for cell counts of PTOX taxa (see Appendix A) and toxins. Lake samples collected after that date are analyzed for toxins only. As described in the section entitled “Recreational Swimming Advisories,” the VDH announces recreational contact (swimming) advisories based on the results of their water analyses.

<u>Reported Blooms and Follow-up Actions</u>
Table 6 summarizes the number of potential HAB reports submitted to VDH by the public and the follow-up actions resulting from the reports. Figure 2 shows the approximate location where blooms were reported. Prior to 2020, the VDH did not receive a single report of a potential HAB on SML, although the Ferrum College annual reports of monitoring on SML occasionally mention a bloom sighting reported to them or observed by them. The first bloom report to VDH for SML occurred in 2020 within the Blackwater arm. Two water samples were collected, but no potentially toxigenic cyanobacteria were observed in the samples. The following year, 2021,

there were five bloom reports submitted to VDH: three on the eastern side of the lake and two on the western side (Bull Run). Some submitted photos appear to show cyanobacterial blooms, but no water samples were collected and analyzed by VDH. Microscopy at Ferrum College revealed a potentially toxin-producing cyanobacteria (*Dolichospermum circinale*) in one bloom (Bull Run), but neither enumeration (cell counts) or toxin testing was performed by Ferrum College. In 2022, two water samples, one from the surface and one in the water column under "scum," were collected by DEQ in the upper Blackwater. Cell counts for potentially toxin-producing cyanobacteria were found in these samples (*Pseudanabaena* sp., *Aphanizomenon* sp.), but the numbers were too low to trigger further action. Approximately a month later, a bloom report was submitted from the east side of the lake (Cedar Key No Wake Buoys), but a water sample was not collected.

Table 6. Annual number of potential HAB-related reports submitted to VDH, number of follow-up water samples analyzed for PTOX taxa/toxins, and whether or not a recreational advisory was issued following the analyses.

Year(s)	# reports submitted to VDH from public	# water samples analyzed for PTOX taxa/toxins	Recreational advisory issued by VDH
<2020	0	0	No
2020	1	2	No
2021	5	0	No
2022	1	2	No
2023	48	28	Yes
2024	3	0	No

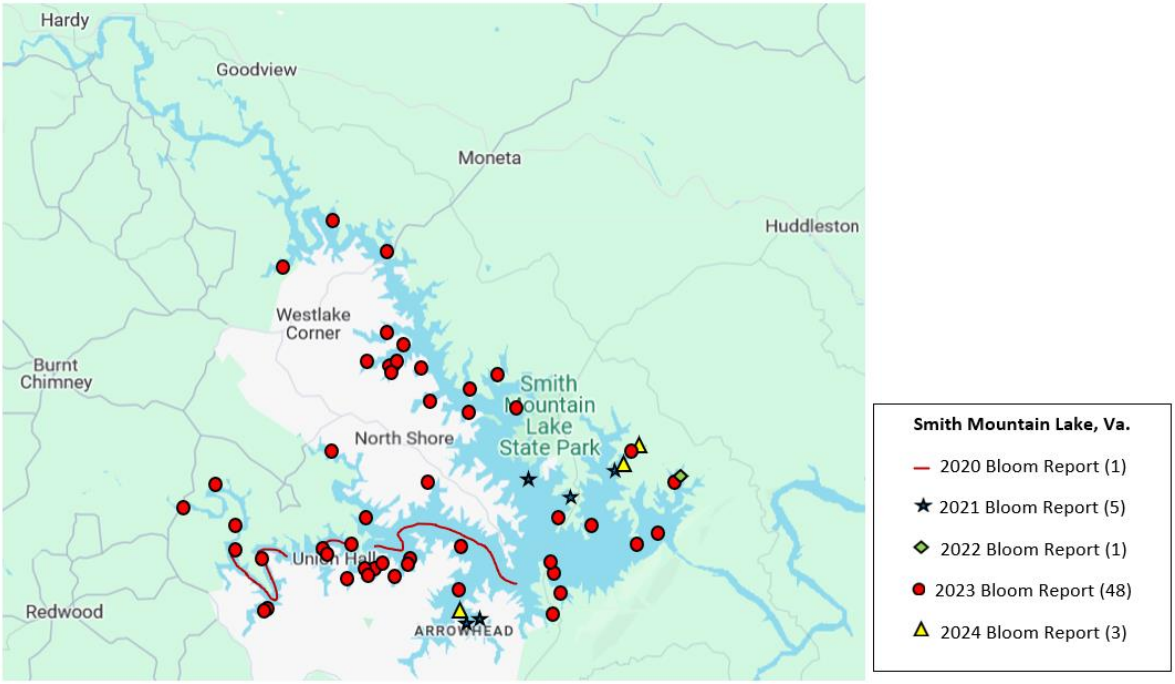

Figure 2. Symbols represent approximate locations where potential HABs on Smith Mountain Lake were reported to VDH from 2020 to 2024.

It is clear in Table 6 that 2023 was different from all other years. Approximately 50 reports of potential cyanotoxin blooms were submitted to VDH in 2023. The majority were in the Blackwater arm, but numerous reports along both sides of the Roanoke arm were also made, as were reports from the Craddock Creek and dam regions of the lake. Almost 30 water samples were collected and analyzed for cell counts of PTOX taxa and toxins. The first water sample collected in 2023 for HAB analysis was from the Blackwater arm on May 23, 2023. The lab found 26,460 cells/mL of total PTOX cyanobacteria taxa, well below the advisory threshold of 100,000 cells/mL. The PTOX taxa found included *Chrysosporum*-like (*Aphanizomenon*)/ *Sphaerospermopsis*-like filament (15,440 cells/mL) and *Dolichospermum circinale* (11,020 cells/mL). The four tested toxins – microcystin, cylindrospermopsin, anatoxin-*a*, and saxitoxin – were below the detection limit of the laboratory methodology. More reports of blooms were submitted in the following days.

The DEQ collected three water samples from the Blackwater arm on June 1, 2023, and once analyzed, VDH announced a recreational advisory on June 6, 2023 for the entire Blackwater arm. All three samples exceeded 100,000 cells/mL with one site (Anthony Ford) exceeding 1,000,000 cells/mL of PTOX taxa. The observed taxa included *Chrysosporum*-like (*Aphanizomenon*)/*Sphaerospermopsis*-like filament, *Dolichospermum circinale*, and at one site (Anthony Ford), *Lyngbya* sp. All three samples had measurable levels of microcystin and anatoxin-*a*, both exceeding 1 µg/L at the Anthony Ford site but well below the threshold level of 8 µg/L needed to trigger an advisory.

Prior to May 22, 2025, the guidance used by VDH specified thresholds for both cell counts of potentially toxin-producing taxa (PTOX) of cyanobacteria and toxin concentrations, and advisories were recommended when any concentration of PTOX taxa or toxin equaled or exceeded the respective threshold listed in Table 2. Based on the June 2023 sampling results, VDH issued a recreational advisory in the Blackwater arm due to PTOX taxa above 100,000 cells/mL. Figure 3 shows the status report by VDH.

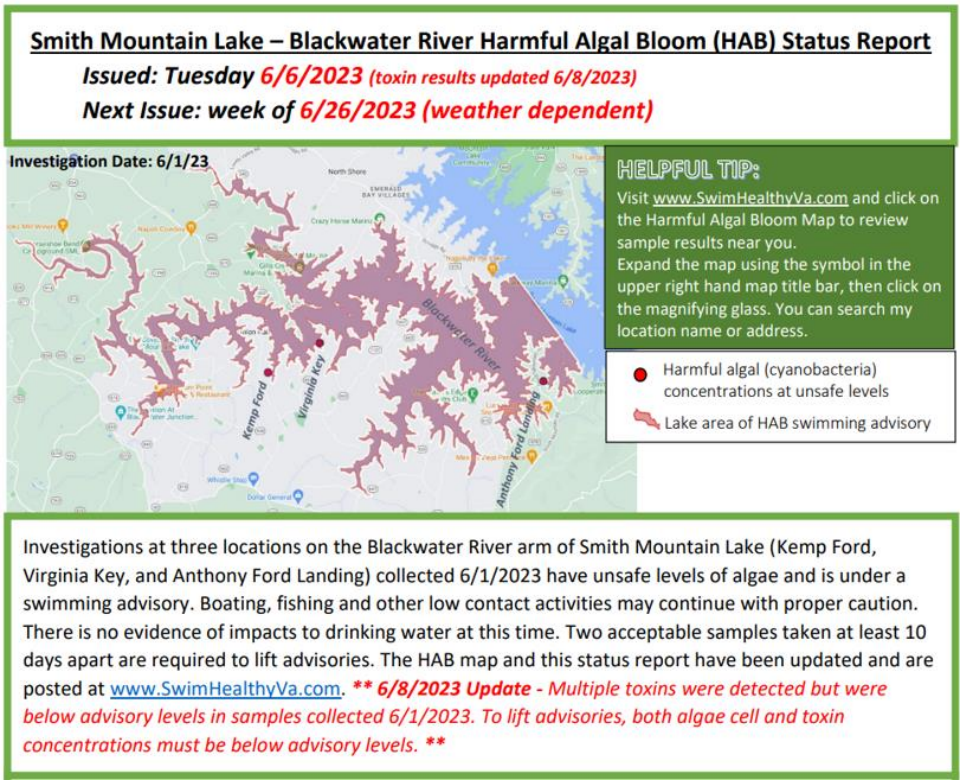

Figure 3. June 6, 2023 HAB status report on the Blackwater arm of Smith Mountain Lake issued by the Virginia Department of Health.

Nine more water samples were collected along the Blackwater arm on June 13, 2023, with lab results announced on June 22, 2023. Four samples taken in the upper Blackwater exceeded 100,000 cells/mL, but a sample from Gills Creek and four samples in the lower Blackwater were below this threshold. As with the earlier samples, the following PTOX taxa dominated: *Chrysosporum*-like (*Aphanizomenon*)/*Sphaerospermopsis*-like filament. All measured toxin levels were below detection. Because two acceptable samples taken at least 10 days apart were needed to remove an advisory, the recreational advisory remained in effect.

From June 15, 2023 to June 19, 2023, eleven reports of blooms were made along the Roanoke arm. Additionally, five bloom reports were submitted in the Blackwater arm from June 18, 2023 to June 24, 2023. No water samples were collected, however.

The next round of sampling occurred on June 26, 2023 in the lower Blackwater. Four water samples were collected, and all were below the threshold level of 100,000 cells/mL. *Chrysosporum*-like (*Aphanizomenon*)/*Sphaerospermopsis*-like filament continued to dominate. Only one site (Anthony Ford) had a detectable level of toxin (microcystin: 0.25 µg/L), which is far below the threshold level that triggers an advisory. Based on these findings, the swim advisory was lifted in Gills Creek and the lower Blackwater on July 7, 2023. The swim advisory remained in the upper Blackwater (Figure 4).

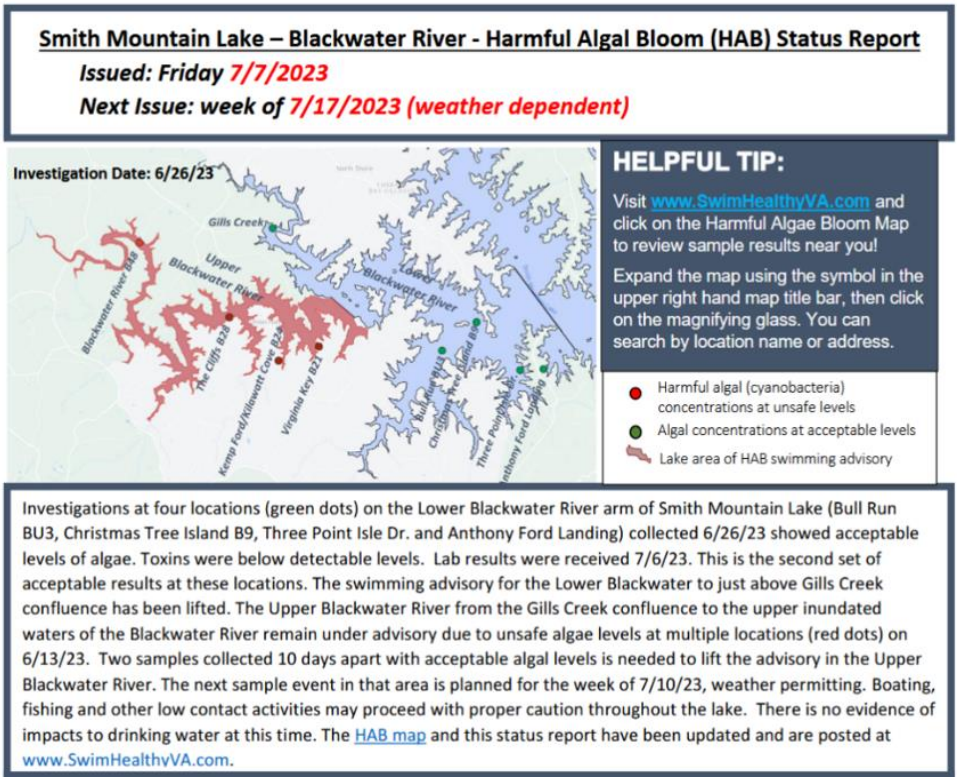

Figure 4. July 7, 2023 HAB status report on the Blackwater arm of Smith Mountain Lake issued by the Virginia Department of Health.

The DEQ collected a water sample at one of their monitoring stations (4AROA180.21) on the Roanoke arm on July 6, 2023. The total PTOX cyanobacteria taxa equaled 2,750 cells/mL (*Chrysosporum*-like (*Aphanizomenon*)/*Sphaerospermopsis*-like filament: 1,770 cells/mL; *Chrysosporum* sp.: 980 cells/mL), and no toxins were detected. Given that no thresholds were exceeded, a swim advisory was not issued. Later in July, a bloom report was submitted for Becky's Creek (Roanoke arm; July 17, 2023), and in August, a report of illness for an entire family after swimming in Indian Creek (Roanoke arm; August 2, 2023) was submitted to VDH. However, no water samples were collected for VDH at these locations for potential HAB analysis. Two other reports of potential blooms were made in Craddock Creek in August 2023, but no water samples were collected.

Four reports of blooms were submitted to VDH on the Blackwater arm in July 2023, and one bloom was identified by Ferrum as *Aphanizomenon*. Five water samples were collected in the upper Blackwater on July 17, 2023. All had total PTOX cell counts below 100,000 cells/mL, and all but one toxin analysis was below the detection limit. The diversity of PTOX taxa in the samples increased. *Chrysosporum*-like (*Aphanizomenon*)/*Sphaerospermopsis*-like filament, *Chrysosporum* sp., *Cuspidothrix issatschenkoi*, *Microcystis wesenbergii*, and *Nostocalean* filament were found in at least one sample. *Chrysosporum*-like (*Aphanizomenon*)/ *Sphaerospermopsis*-like filament continued to dominate at three sites. *Microcystis wesenbergii* (14,500 cells/mL) and *Cuspidothrix issatschenkoi* (12,000 cells/mL) dominated at the uppermost collection station (DEQ Monitoring Site: 4ABWR017.42), and *Cuspidothrix issatschenkoi* (600 cells/mL) was the only identified PTOX taxa at Channel Marker B22. Although the cell counts

were not high at Channel Marker B22, a low, but measurable, level of microcystin was found (0.17 µg/L).

By mid-August, water samples collected on the Blackwater arm allowed for the recreational advisory to be lifted. Of the five samples collected on August 15, 2023, all had PTOX taxa, but all were below the threshold of 100,000 cells/mL. The lowest cell counts of PTOX taxa were at Horseshoe Bend (DEQ Monitoring Site: 4ABWR017.42) at 150 cells/mL, and the highest cell counts for PTOX taxa were at Channel Marker B16 at 39,162 cells/mL. All five samples contained *Chrysosporum*-like (*Aphanizomenon*)/*Sphaerospermopsis*-like filament. Channel Marker B37 also had *Cuspidothrix issatschenkoi*, *Nostocalean* filament, and *Raphidiopsis* sp. Two other sites also had *Nostocalean* filament and *Raphidiopsis* sp. Among the five water samples collected, three sites had measurable levels of microcystin, two had measurable concentrations of saxitoxin, and one site had measurable amounts of anatoxin-*a*; but all were well below the threshold limits for a recreational advisory. Only at Horseshoe Bend (DEQ Monitoring Site: 4ABWR017.42) were all toxin levels below the limit of detection. Given these results, the recreational advisory was lifted by VDH on August 24, 2023 (Figure 5).

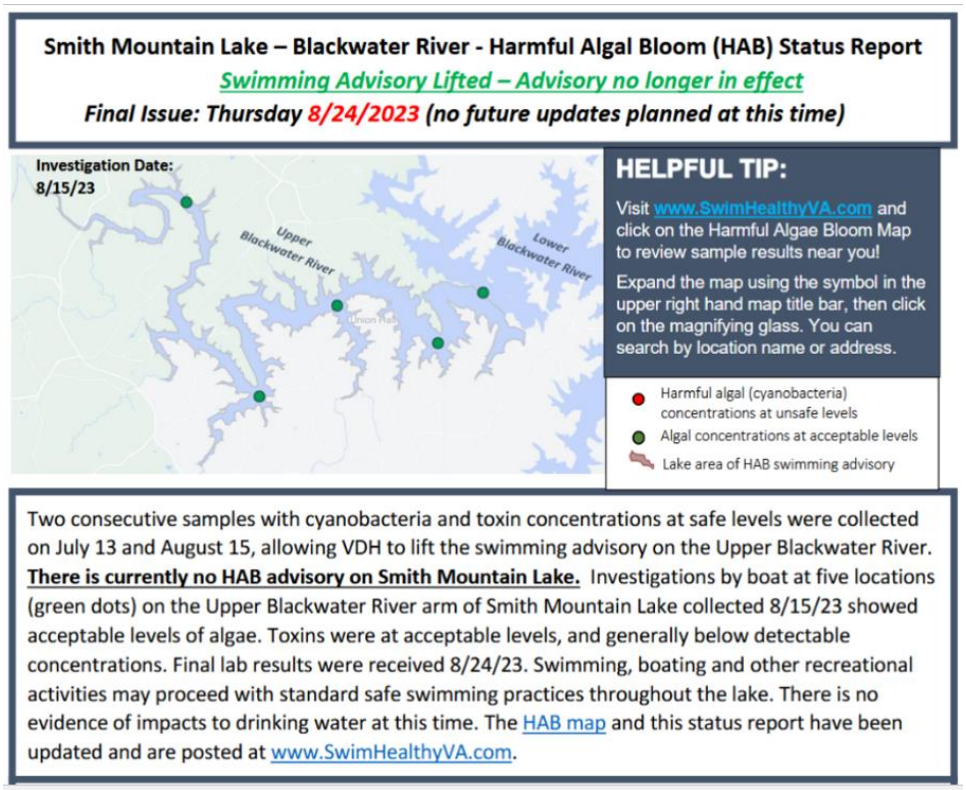

Figure 5. August 24, 2023 HAB status report on the Blackwater arm of Smith Mountain Lake issued by the Virginia Department of Health. This report signaled the lifting of the recreational advisory for the upper Blackwater arm.

A final bloom report was submitted to VDH in 2023 in October. The report stated that an entire cove near Channel Marker B-21 on the Blackwater arm was affected by a "light streaking, entrained material in the water column." The report added that a phycocyanin meter reading of

37 was detected and noted that during active blooms in the summer the readings ranged from 15-20 (units were not provided; assumed to be RFUs [relative fluorescence units]).

Given the prolonged HAB and recreational (no swim) advisory in the Blackwater arm in 2023, there was concern that 2024 could see a repeated pattern of blooms. Fortunately, this is not what occurred. There were only three bloom reports submitted to VDH in 2024. One bloom report was submitted in 2024 from the upper reaches of Craddock Creek in March, and the second report came from Bull Run in April. The third report was submitted in August and indicated an illness in an individual who swam in the lake and noted that the water was "noticeably green and different looking after a storm" the previous day. The VDH was unable to confirm the location of this report, which was listed as off "Preston Street," but is believed to be near Preston Drive in the Craddock Creek region. No water samples were collected for PTOX taxa or toxin analysis in 2024.

Reported Illnesses and Follow-up Action

In 2023 and 2024, the VDH received six reports from the public of illness after swimming in SML although HAB toxicity was not confirmed. At least one person sought medical attention for their symptoms (Table 7). When possible, VDH personnel reached out to individuals making reports.

Table 7. Reports of illnesses after swimming in Smith Mountain Lake.

Swim Date	Swim Location	Lake Area	Symptoms reported after swimming in SML	Notes
6/3/2023	Bull Run	Blackwater	Individual reported feeling dizzy, dehydrated, and unable to keep down food or water; lost 9 pounds between 6/3 to 6/5.	Reported noticing green water (thought it was pollen). Symptoms began 3 h after contact; went to Blue Hills ER at 4:45 a.m. on 6/5/2023; treated with fluids and nausea medicine. Area where person swam was included in the no-swim advisory once declared on June 6, 2023 (from water samples collected June 1, 2023).
6/9/2023	37°01'34.8"N, 79°41'02.2"W	Blackwater	Individual reported skin irritation -- burning sensation (like sun burn)	Reported seeing suspected HAB 2-3 weeks prior to and days after swimming. Time and location correspond to the no-swim advisory for the Blackwater River.
6/12/2023	Near Dam; 37°02'42.5"N, 79°32'19.8"W	Mid-channel	Individual reported skin irritation -- itchy rash with blisters; swollen eye lids	Swim area is outside the no-swim advisory but during the time period of the advisory.
6/18/2023	SML State Park; 37°05'36.0"N, 79°36'28.6"W	Roanoke	Couple reported vomiting and diarrhea 3 days after swimming in lake	Gastrointestinal symptoms after oral exposure to cyanobacteria are usually within 3–5 hours, indicating potential other reason for illness.
8/2/2023	37°08'31.5"N, 79°42'56.6"W	Roanoke	Entire family reported vomiting and diarrhea	Reported no visible signs of a bloom, but area "smelled musty."
8/9/2024	Reported as Preston St. -- Possibly Craddock Creek	Unknown	Individual reported "an illness"	Reported seeing green water that looked different after 8/8/2024 storm.

Reports on Impacts to Wildlife

Harmful algal blooms not only affect humans, but they can also impact domestic animals and wildlife. Bloom reports submitted to VDH included two incidences where dead fish were observed in the water, although HAB toxicity was not confirmed.

- 6/1/2023 (Anthony Ford area) – The submitter reported seeing at least one dead fish in the middle of a 500–1000 sq. ft. bloom. Water samples collected near this location on the same day had the highest cell counts obtained for SML (1,489,380 cells/mL of PTOX taxa) and highest levels of toxins (microcystin: 1.05 µg/L and anatoxin-*a*: 1.26 µg/L).
- 6/17/2023 (Gills Creek area) – The submitter reported observing several dead fish in a cove but no visible evidence of a bloom. Scum was present on the water the following two days. No water samples were collected.

Conclusions from Reports

While VDH has received reports of potential HAB events in Smith Mountain Lake since 2020, the year 2023 stands out for the number of potential HABs that were reported. The VDH issued a swimming advisory in the Blackwater arm of SML in 2023 as a result of elevated cell counts of potentially toxin-producing taxa (PTOX) of cyanobacteria, but cyanotoxins were not reported near or above VDH thresholds. Since 2023, VDH has not issued swimming advisories in SML.

The reports submitted to VDH in 2023 and swimming advisory issued by VDH in 2023 illustrate that SML has the potential to support multiple and prolonged HAB events when conditions are favorable for the growth of cyanobacteria. Cyanobacterial blooms have the potential to negatively impact human health and wildlife and thereby stress the importance of continual assessment of the water and the need for recreational advisories when VDH thresholds are exceeded. However, the reports do not indicate a consistent pattern of blooms. The increased number of reports to VDH since 2020 is likely due to a combination of factors, including more people being aware of blooms, more people knowing how to report blooms and illnesses, and an increasing number of blooms within the lake.

The reports also show that blooms can occur in any region of the lake but are most common and have shown the highest cell counts of potentially toxin-producing taxa (PTOX) of cyanobacteria in the Blackwater arm. Also, most reports locate blooms within shallow coves, which provide ideal growing conditions for cyanobacteria and where blooms are easily visible to people.

Objective 1, Task 2: Remotely Sensed Bloom Analysis

Traditional monitoring methods, based on field sampling and laboratory analysis, are resource-intensive and offer limited spatial coverage. As a result, it is often difficult in capturing the onset, extent, and progression of bloom events in a timely and cost-effective manner. Remote sensing offers a compelling complement to in situ monitoring by enabling synoptic, repeatable observations of water quality indicators over broad areas. Among the most effective satellite-derived metrics for bloom detection are chlorophyll-related indices such as the Normalized Difference Chlorophyll Index (NDCI) (Mishra & Mishra, 2012). This index uses the distinct spectral signatures of algal pigments in the red, red-edge, and near-infrared bands, allowing for direct identification of chlorophyll-rich surface waters. The use of NDCI has been validated

across diverse aquatic systems, from coastal zones to turbid inland lakes, and it has proven sensitive to both phytoplankton abundance and bloom severity (Kutser et al., 2006; Vanhellemont & Ruddick, 2016). Sentinel-2 imagery has 10-meter spatial resolution and a 5-day revisiting time. The fine spatial detail is particularly important for SML's narrow tributary arms. Moreover, remote sensing enables the development of consistent historical bloom records, which are essential for trend analysis, early warning, model validation, and the assessment of watershed nutrient management efforts.

Data Sources and Cloud Filtering

We explored the utility of remote sensing for bloom identification in SML by focusing on the growing season of 2023 when blooms were consistently present. We utilized the Sentinel-2 Level-2A Surface Reflectance product (S2-SR) and filtered the image collection by our area of interest (AOI) and a seasonal date range from May to August 2023. To ensure data quality, we applied a two-stage cloud filtering process. First, we masked cloud-contaminated pixels at the scene level using the Scene Classification Layer (SCL) produced by the Sen2Cor processor. Specifically, we excluded pixels labeled as cloud shadow (class 3), low/medium/high-probability cloud (classes 7–9), and thin cirrus (class 10), following the classifications defined in the Sen2Cor Algorithm Theoretical Basis Document (European Space Agency, 2021). Second, we removed entire scenes with excessive cloud cover using the CLOUDY_PIXEL_PERCENTAGE metadata field. Scenes exceeding a 50% cloud cover threshold were discarded, consistent with standard practices where the maxCloudCoverage parameter is typically set between 20% and 50% to avoid overly cloudy scenes (Sentinel Hub, 2024).

Normalized Difference Chlorophyll Index (NDCI) Assessment

We calculated the NDCI to estimate chlorophyll-*a* concentrations in SML. The NDCI is defined as:

$$NDCI = (B8A - B4) / (B8A + B4)$$

B8A represents reflectance in the red-edge spectral band, while B4 corresponds to the red spectral band. Positive NDCI values indicate chlorophyll-rich waters. In our analysis, we report the continuous values but also applied a binary mask with NDCI > 0 to delineate bloom-affected areas. This threshold has been used in previous studies to map bloom extent and severity, including investigations of coastal fish mortality events and inland lake monitoring (e.g., Binding et al., 2018; EIForum, 2023). We note that while NDCI is a useful proxy for chlorophyll concentration, it may not directly correlate with the presence of HABs, which require additional biological or chemical confirmation.

We derived NDCI images for nine dates in 2023: May 8, June 2, June 17, July 12, July 27, August 1, August 11, August 16, and August 26. These images capture the spatial distribution of chlorophyll concentrations across SML during the peak bloom season. The outputs, systematically named (e.g., SMLake_20230508_NDCI_utm17n.tif), provide high-resolution snapshots of bloom dynamics at a 10-meter resolution. One of these images, from June 2, was integrated into the webtool for interactive visualization. Figure 6 displays the NDCI values in

both continuous form (a) and binary form (b), with the latter highlighting areas exceeding the threshold for elevated chlorophyll levels. All other image dates are stored in GeoTIFF format and available for distribution.

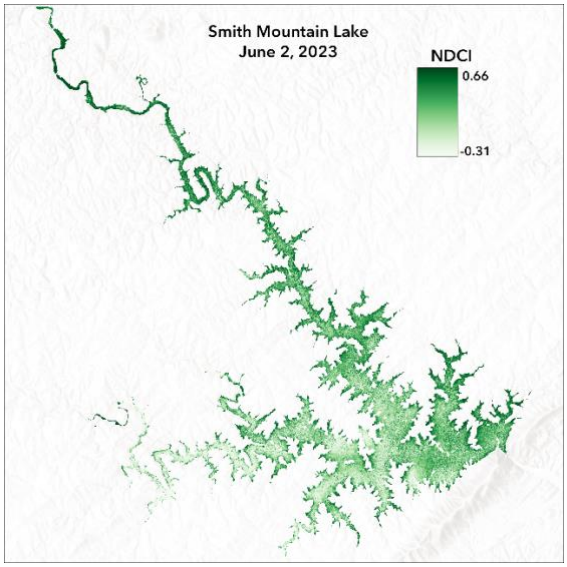

Figure 6a. NDCI values on June 2, 2023.

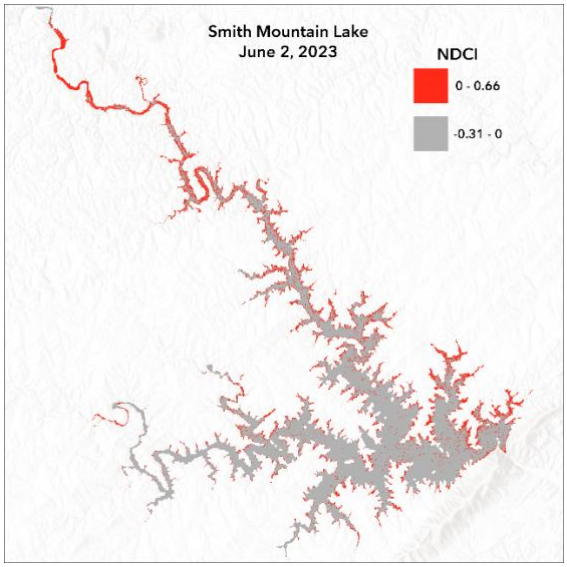

Figure 6b. NDCI values above (red) and below (grey) the threshold (0) for elevated chlorophyll on June 2, 2023.

Objective 2: Identify the major factors and conditions leading to the occurrence of HABs in SML

Both natural and anthropogenic drivers, such as weather conditions and land use, affect lake conditions that lead to or prevent cyanobacterial blooms and potential HAB formation. Typical factors that influence the development of HABs include available nutrients (particularly nitrogen and phosphorus), sunlight, temperature, turbidity, water chemistry (pH, conductivity), and hydrology (flow, velocity, turbulence). This work utilized available watershed and lake condition data, including hydrologic, land-use, and water quality data. There are three tasks to meet this objective: Task 1) compile and analyze available water quality data for SML; Task 2) conduct a detailed land-use analysis; Task 3) conduct watershed modeling to quantify sediment and nutrient loadings from non-point sources to SML.

Objective 2, Task 1: Water Quality Analysis

We compiled, reviewed, and evaluated existing water quality data for SML, with a focus on monitoring data provided from DEQ and the SML Water Quality Monitoring Program.

DEQ Monitoring Data

The DEQ water quality dataset includes 22 monitoring sites either within SML or a tributary of SML, with records spanning from 1994 to 2024. Each observation contains detailed information such as station identification code, location description, sampling date and depth, and field notes. Key water quality parameters measured include temperature, pH, dissolved oxygen (DO), specific conductance, nitrogen (total, ammonia, nitrate and nitrite [NO_x], and Kjeldahl), phosphorus (total and orthophosphate), total hardness, chloride, sulfate, and multiple bacterial indicators (e.g., *E. coli*, fecal coliform). Additional parameters include chlorophyll-*a*, total suspended solids (TSS), and Secchi depth. Each record also includes latitude, longitude, and classification codes for station grouping. A total of 62,186 water quality records were imported into the PostGIS database, enabling efficient querying, statistical analysis, and interactive visualization. Here, we present a summary of long-term trends in water quality variables and correlations between variables. The webtool provides the full dataset for each station and allows users to examine long-term trends and between-variable correlations for each station.

Across the DEQ monitoring network, sampling dates and depths vary. To account for this, we first standardized each variable into a regular, calendar-month time series before estimating trends. Specifically, for each station and variable (e.g., pH, temperature, nutrients), we grouped observations by month and calculated the average within each month. This aggregation yields an evenly spaced series, one value per month, that balances months with many visits against those with few.

Long-term Water Quality Trends

We statistically analyzed long-term DEQ water-quality data for SML to identify changes and determine the significance of trends. Stations with less than 5 years of data were not included in the trend analysis. A description of the methods used and results for each analyzed station are provided in Appendix D.

Sen's Slope analysis was conducted to assess temporal trends in key water quality parameters in SML. This method provides a robust estimate of the rate of change over time, allowing for the detection of increasing or decreasing trends. A positive slope indicates an upward or increasing trend in the data over time, and a negative slope signifies a decreasing trend over time. The magnitude of the slope indicates the rate of change, with values furthest from zero (positive or negative numbers) indicating steeper slopes and more rapid change. We complemented the Sen's Slope analysis with the Mann–Kendall test to assess whether the trend indicates a significant or non-significant change ($\alpha = 0.05$). Significant results ($p < 0.05$) indicate the change is meaningful and real (not likely the result of random chance).

Here, we summarize long-term trends for fifteen stations located across SML and four stations located upstream of SML (Route 812 Bridge [Blackwater], Route 834 Bridge [Gills Creek], Route 757 Bridge [Beaverdam Creek], and Blue Ridge Parkway Bridge [Roanoke]; Figure 7). For each station, the Sen's slope is provided for all significant trends (Table 8 and Table 9). Blank spaces in the tables indicate the trend was not significant, and "xx" indicates a lack of data for the parameter.

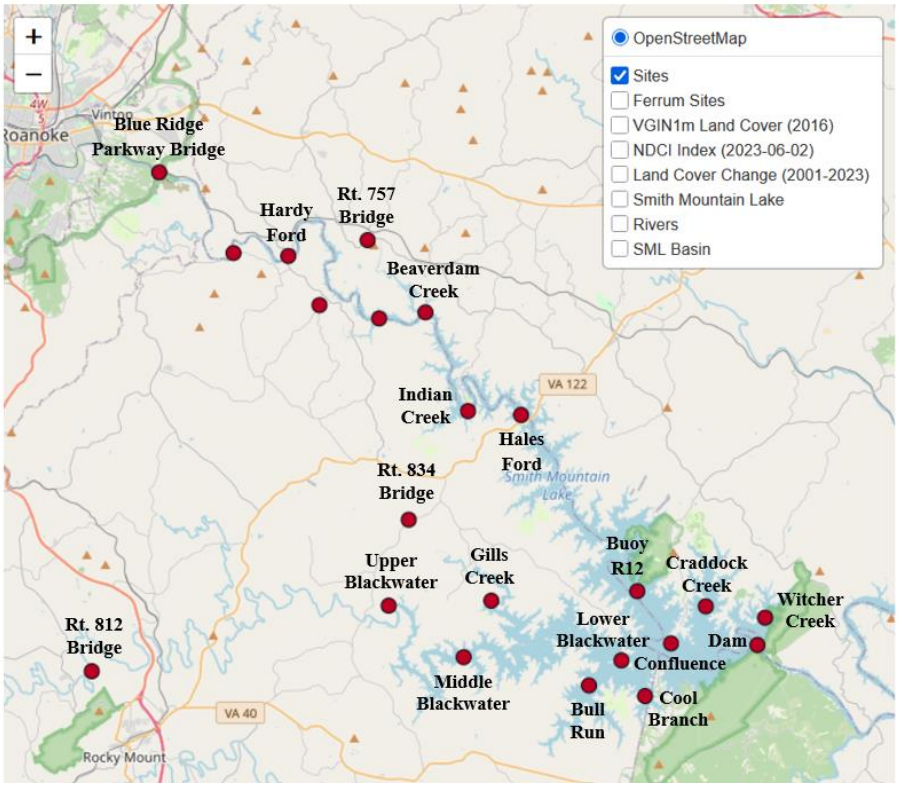

Figure 7. Map of Smith Mountain Lake with DEQ monitoring stations used for trend analysis.

Table 8. Sen's slopes (per decade) for significant trends within stations on Smith Mountain Lake that have at least 5 years of data.

	Station	Temp (°C)	Nitrogen (mg/L)	Ammonia (mg/L)	NO_x (mg/L)	TKN (mg/L)	TP (mg/L)	Hardness (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Chl-*a* (µg/L)	DO (mg/L)	pH	TSS (mg/L)
Main	Dam (4AROA158.22)	1.25	-0.09	-0.01	-0.06		-0.00	-16.05		3.46	0.27		-0.16	-1.54
	Mouth of Witcher Cr. (4AWTH000.40)	0.94	-0.08	-0.01	-0.06		0.00				0.36		-0.11	
	Mouth Craddock Cr. (4ACCK001.80)	0.95	-0.08	-0.01	-0.06		-0.00			2.59	0.25		-0.14	
	Confluence: Roanoke & Blackwater (4AROA163.76)	1.39	-0.07	-0.01	-0.05	-0.02	0.00			3.38	0.27		-0.10	-0.42
Blackwater	Lower Blackwater (4ABWR002.50)	1.51	-0.09	-0.01	-0.06	-0.04	0.00			3.28	0.29		-0.09	-0.72
	Middle Blackwater (4ABWR010.55)	1.19	-0.08	-0.01	-0.07		-0.00		2.85	3.27	1.26		-0.12	
	Upper Blackwater (4ABWR017.42)	0.73	-0.04	-0.01	-0.02		0.00		3.37	1.16			-0.18	
	Cool Branch (4ACOA000.60)	0.97	-0.10	-0.01	-0.06		0.00		2.33	3.50			-0.13	
	Mouth of Bull Run (4ABSA000.62)	1.09	-0.09	-0.01	-0.06		0.00		2.66	3.52			-0.13	-0.81
	Gills Creek (4AGIL002.39)		-0.06	-0.02	-0.03		-0.00		5.19	5.52		-0.71	-0.22	
Roanoke	Buoy R12 (4AROA167.34)	1.32	-0.10	-0.01	-0.07		-0.00	-33.50		3.56		0.50	-0.15	
	Hales Ford (4AROA175.63)	0.97	-0.08	-0.02	-0.04		-0.00	-42.21		5.92	1.23		-0.18	
	Confluence: Indian Cr. (4AROA180.21)	0.81	-0.08	-0.03	-0.04		-0.00	-45.43		8.00	1.23		-0.17	
	Confluence: Beaverdam Creek (4AROA183.64)	0.94	-0.08	-0.03			-0.00			7.58			-0.16	
	Hardy Ford (4AROA192.94)			-0.01	0.11		-0.01			14.32	-1.18		-0.13	

NO_x = nitrate and nitrite; TKN = total Kjeldahl nitrogen; TP = total phosphorus; Hardness = Total Hardness; Chl-*a* = chlorophyll-*a*; DO = dissolved oxygen; TSS = total suspended solids

Table 9. Sen's slopes (per decade) for significant trends within stations upstream of Smith Mountain Lake that have at least 5 years of data.

Station	Temp (ºC)	Nitrogen (mg/L)	Ammonia (mg/L)	NO_x (mg/L)	TKN (mg/L)	TP (mg/L)	Total Hardness (mg/L)	Sulfate (mg/L)	Chloride (mg/L)	Chl-a (µg/L)	DO (mg/L)	pH	TSS (mg/L)
Blackwater, Rt. 812 Bridge (4ABWR045.80)		-0.06	0.00	0.13	-0.08	-0.02		-0.67	-0.66	xx	0.42	-0.06	-1.01
Gills Creek, Rt. 834 Bridge (4AGIL008.30)			-0.02				xx	xx	xx		1.26		-5.58
Beaverdam Cr., Rt. 757 Bridge (4ABDA004.14)			xx	xx	xx		xx	xx	xx	xx		-0.80	xx
Roanoke, Blue Ridge Parkway Bridge (4AROA199.20)								xx	xx	xx		0.19	

Temp = Temperature; NO_x = nitrate and nitrite; TKN = total Kjeldahl nitrogen; TP = total phosphorus; Chl-*a* = chlorophyll-*a*; DO = dissolved oxygen; TSS = total suspended solids; xx = no data

Temperature: Higher water temperatures provide more favorable growing conditions for cyanobacteria (Carey et al., 2012; Paerl, 2014) and therefore are of interest when considering how best to manage cyanobacterial blooms.

Surface water temperatures increased significantly at 13 stations on SML, with Sen's slope estimates for these sites ranging from 0.73 to 1.51 °C per decade (or 1.31 to 2.72 °F per decade). Most stations exhibited warming rates near 1.0 °C per decade (1.8 °F per decade), consistent with broader regional climate patterns. Only Gills Creek and Hardy Ford stations on SML had non-significant temperature changes, and all four upstream stations (Blackwater, Gills Creek, Beaverdam Creek, and Roanoke) had non-significant temperature changes. Using DEQ data from SML and other reservoirs across Virginia, Bukaveckas et al. (2025) found warming trends in both surface and bottom layers. They also found longitudinal differences in surface water temperatures, with SML having the largest differences among the Virginia reservoirs in the study.

Nitrogen: Nitrogen in water exists in different forms and therefore can be measured in several ways. Ammonia (NH_3), nitrate (NO_3^-), and nitrite (NO_2^-) are inorganic forms of nitrogen. Nitrate and nitrite are collectively referred to as NO_x. Concentrations of total Kjeldahl nitrogen (TKN) reflect organic nitrogen and ammonia in a water sample, and total nitrogen (TN) concentrations measure all organic and inorganic forms of nitrogen in a water sample. For this analysis, nitrogen concentrations signify direct measurements of TN, or when TN was not directly measured, by combining the concentrations of TKN and NO_x.

For cyanobacteria, nitrogen is an essential macronutrient, meaning it is needed in large quantities. Ammonia can be utilized directly by cyanobacteria (and other primary producers) so is the preferred form of nitrogen used. However, many cyanobacteria can convert other kinds of nitrogen into useable forms. For example, some species of cyanobacteria can convert nitrate and nitrite into ammonia for use as a nitrogen source, but such conversions are energy-intensive so they prefer taking ammonia directly from the water when available. Some cyanobacteria species can fix nitrogen directly from the air, meaning they can convert atmospheric nitrogen (N_2) into ammonia for use within the cell. Fixing nitrogen is energetically expensive (requires the breaking of a triple bond) so it is utilized only when other forms of nitrogen are unavailable.

Fifteen of the nineteen stations that were analyzed had significant downward trends for nitrogen (1994–2024), with Sen's slopes ranging from -0.10 to -0.04 mg L^{-1} $decade^{-1}$. On SML, all stations had declining nitrogen trends except for the Hardy Ford station, which had non-significant trend results. Among the stations upstream of SML, the station on the Blackwater at the Route 812 Bridge had significantly decreasing nitrogen levels (-0.06 mg L^{-1} $decade^{-1}$); the other three stations had non-significant trends.

Ammonia trends declined slightly from 1994 to 2024 for all 15 analyzed stations on SML, with Sen's slopes ranging from -0.03 to -0.01 mg L^{-1} $decade^{-1}$. All trends were statistically significant ($p < 0.05$). The upstream stations on the Blackwater and Gills Creek also had significant but small decreasing ammonia trends, with Sen's slopes approximating 0 mg L^{-1} $decade^{-1}$ for the Blackwater at the Route 812 Bridge and -0.02 mg L^{-1} $decade^{-1}$ for Gills Creek at the Route 834 Bridge.

Most stations on SML had significant downward trends for nitrate and nitrite (NO_x) data obtained from 1994 to 2024, with slopes ranging from -0.07 to -0.02 mg L^{-1} $decade^{-1}$. The two exceptions included Hardy Ford, which had a significant increasing trend for NO_x (Sen's slope: 0.11 mg L^{-1} $decade^{-1}$), and the station at the confluence with Beaverdam Creek, which did not have a significant trend for NO_x. Among the upstream stations, the one on the Blackwater (Route 812 Bridge) exhibited a significant increasing NO_x trend, with a slope at 0.13 mg L^{-1} $decade^{-1}$.

Total Kjeldahl nitrogen (TKN) trends (1994–2003) declined significantly at two stations on SML: the confluence of the Roanoke and Blackwater arms (Sen's slope: -0.02 mg L^{-1} $decade^{-1}$) and the lower Blackwater (Sen's slope: -0.04 mg L^{-1} $decade^{-1}$). Likewise, the TKN trend for the upstream station on the Blackwater (Route 812 bridge) significantly declined (Sen's slope: -0.08 mg L^{-1} $decade^{-1}$).

Phosphorus: Phosphorus is an essential macronutrient required by cyanobacteria. Orthophosphate (PO_4^{3-}) is a dissolved, inorganic form of phosphorus that cyanobacteria (and other primary producers) preferentially use. Total phosphorus (TP) measures organic and inorganic forms of phosphorus, in both dissolved (soluble) and particulate (bound to suspended particles) phases.

The World Health Organization's *Guidelines on Recreational Water Quality: Volume 1 Coastal and Fresh Waters* (World Health Organization, 2021) states, "blooms of significance to recreational exposure usually require TP concentrations above 20–50 µg/L." Many station averages on SML exceed 20 µg/L (0.02 mg/L), especially in the upper reaches of the Blackwater and Roanoke arms, but none of the stations on SML in this dataset currently exceed 50 µg/L on average. However, almost all stations on SML have individual samples that exceed 50 µg/L. Such pulses of phosphorus could be of importance, given the ability of some cyanobacteria to store phosphorus for use in periods of limiting phosphorus availability.

Strong downward trends for total phosphorus concentrations are needed in SML to expeditiously meet the goal of less than 20 µg/L. However, trends for total phosphorus concentrations in SML (1994–2024), while significant, only declined slightly at nine stations on SML (Sen's slope estimates ranged from -0.01 to approximately 0 mg L^{-1} $decade^{-1}$). Six additional stations on SML had significant differences for total phosphorus but had Sen's slopes approximating 0 mg L^{-1} $decade^{-1}$ (mouth of Witcher Creek, confluence of Blackwater and Roanoke, lower and upper Blackwater, Cool Branch, and mouth of Bull Run). The results for these six stations imply that the phosphorus concentrations are not consistently increasing or decreasing over time. Among the four stations upstream of SML, only the Blackwater station (Route 812 Bridge) had a significant phosphorus trend, which was decreasing (Sen's slope: -0.02 mg L^{-1} $decade^{-1}$).

Total Hardness: Total hardness concentrations primarily measure magnesium and calcium in the water. Magnesium is a vital macronutrient for cyanobacteria. Among other roles, magnesium is essential to the formation of the chlorophyll molecule, the pigment essential for photosynthesis. Because cyanobacteria are photosynthetic, they require large quantities of chlorophyll and thus magnesium. Calcium is a micronutrient (needed in small quantities) that is involved in numerous cellular processes, including photosynthesis. Although required in lesser quantities compared to magnesium, calcium is also necessary for cyanobacterial growth.

Total hardness concentrations declined significantly at the station by the dam and at three stations on the Roanoke arm (Buoy R12, Hales Ford, and confluence with Indian Creek). The Sen's slope estimates for these four locations ranged from -45.43 to -16.05 mg L^{-1} $decade^{-1}$ during the monitoring period (1997–2003). The results indicate moderate to strong downward trends. These stations on SML have moderately hard water, typically ranging from 60–120 mg/L, so likely have sufficient calcium and magnesium to support cyanobacterial blooms. The exact reasons for the declines in total hardness are beyond the scope of this project but could result from increased precipitation and runoff (causes dilution), reduced groundwater inflow (less input of mineral-rich water), etc. Given that magnesium and calcium are essential for photosynthesis, a reduction in total hardness could also reflect a higher amount of primary productivity, but this scenario is not supported by the chlorophyll-*a* data for these stations during this time period (1997–2003).

Sulfate: Sulfate (SO_4^{2-}) is an essential macronutrient used by cyanobacteria in making amino acids and sulfolipids (essential for photosynthesis). Some genera of cyanobacteria use sulfate to make toxins (e.g., cylindrospermopsin). For example, certain species of *Aphanizomenon,* which dominated the 2023 blooms in SML, can produce toxins that contain a sulfate group. Some species of the cyanobacteria genus *Planktothrix*, also found in SML, have the potential to produce the toxin aeruginosin, which often contains sulfate. Thus, high levels of sulfate in SML may not only promote the formation of cyanobacterial blooms but also the production of toxins.

Five lake stations in the Blackwater arm (middle Blackwater, upper Blackwater, Cool Branch, mouth of Bull Run, and Gills Creek) showed increasing trend slopes for sulfate between 2.33 and 5.19 mg L^{-1} $decade^{-1}$ during the monitoring period (1994–2001). Increasing sulfate trends may indicate accumulating organic matter and increased resuspension processes within the Blackwater arm. Organic matter that settles to the bottom of the lake provides an important nutrient source for sulfate-reducing bacteria that convert sulfate into hydrogen sulfide (H_2S). When the lake mixes during spring and fall turnover or when the bottom sediments are disturbed (e.g., boating activities), hydrogen sulfide within the sediments can be dispersed into the water column and re-oxidized into sulfate.

The most upstream station on the Blackwater, at the Route 812 Bridge, exhibited a significant declining sulfate trend at -0.67 mg L^{-1} $decade^{-1}$. Typical reasons for sulfate levels to decline in a river include reduced atmospheric depositions, increased activity of sulfate-reducing bacteria (especially if the river has high levels of organic matter), increased flows that cause dilution, etc.

Chloride: Chloride is a micronutrient used by cyanobacteria to regulate enzymes, facilitate photosynthesis, and perform other functions. There are typically much higher levels of chloride within the environment than are required by cyanobacteria so chloride is not considered a limiting nutrient to cyanobacterial growth. However, chloride can indirectly promote cyanobacterial blooms.

Road salt used for de-icing in winter can be a major contributor of chloride to lakes. Also, conventional wastewater treatment processes do not remove chlorides so chloride levels can be high in wastewater effluent. Other sources of chloride include industrial effluents, landfill

leachate, synthetic fertilizers, animal waste, and natural sources like weathering rocks with chloride and atmospheric deposition.

High levels of chloride negatively impact many freshwater organisms, including some species of cyanobacteria. However, many cyanobacteria, such as *Microcystis*, are highly tolerant of increasing salinity and can adapt to elevated chloride levels, which gives them a competitive advantage over less tolerant organisms. Additionally, high concentrations of chloride can reduce zooplankton populations that would typically graze on cyanobacteria. Furthermore, high chloride concentrations can affect lake stratification because saline water is denser than freshwater so it sinks to the bottom of the lake and creates a haline (salt) gradient. This haline gradient prevents lake mixing during spring and fall turnover and sets up anoxic (depleted of oxygen) conditions that lead to the release of nutrients and metals from lake sediments into the water column. For these reasons, increases in chloride concentrations could be of concern for SML with respect to cyanobacterial blooms.

The trend for chloride concentrations increased significantly at 14 stations on SML from 1994 to 2001, with Sen's slopes ranging from 1.16 to 14.32 mg L^{-1} $decade^{-1}$. These overall results indicate increasing salinization trends that are also noted regionally. The Hardy Ford station in the upper Roanoke had the steepest slope, indicating the fastest rate of change. This station also had the highest chloride levels among the monitoring stations on SML (approximately 5–35 mg/L). The Hardy Ford station is closest to the City of Roanoke, where numerous potential sources of chloride are expected (the station at the Blue Ridge Parkway Bridge is closer to the City of Roanoke, but there are only two chloride data points for this station [23 and 28 mg/L]).

The chloride trend decreased significantly at the upstream Blackwater station located at the Route 812 Bridge (-0.66 mg L^{-1} $decade^{-1}$). This trend is helpful from a management perspective in reducing cyanobacterial blooms.

Chlorophyll-a: Chlorophyll-*a* is the primary green pigment in cyanobacteria, algae, and plants that is essential for converting sunlight into energy during photosynthesis. Thus, chlorophyll-*a* provides an indication of the amount of primary production occurring within a lake. Chlorophyll-*a* concentrations increased significantly at eight stations on SML, with Sen's slope estimates ranging from 0.25 to 1.26 µg L^{-1} $decade^{-1}$ (1998–2024 monitoring period). Increasing trends in chlorophyll-*a* were observed for four stations in the main section of SML (dam station, mouth of Witcher Creek, mouth of Craddock Creek, and confluence of the Blackwater and Roanoke arms), two stations on the Blackwater (lower and middle Blackwater), and two stations on the Roanoke (Hales Ford, and confluence with Indian Creek). These upward trends in chlorophyll-*a* concentrations suggest rising biomass of primary producers in portions of the monitoring network.

One station, Hardy Ford in the upper region of the Roanoke arm, had a significant downward trend in chlorophyll-*a* (Sen's slope: -1.18 µg L^{-1} $decade^{-1}$), indicting lower primary productivity at that station. Among many possible reasons for this trend, the upward rise in chloride at the Hardy Ford station may offer one reason for this decline. Chloride levels at 10–20 mg/L can negatively impact certain species of primary producers, and this station exceeded this range, with one sample approaching nearly 35 mg/L.

Dissolved Oxygen: During cyanobacterial blooms, water near the surface becomes supersaturated with dissolved oxygen (DO), meaning the water holds higher levels of oxygen than expected for the given water temperature (cold water holds more oxygen than does warm water). This condition results because oxygen is a waste product of photosynthesis and is deposited into the water by primary producers. When photosynthesis takes place at high levels in a lake, river, or stream, the water within the photic zone (where sunlight penetrates sufficiently to support photosynthesis) becomes supersaturated with oxygen. This phenomenon occurs because primary producers generate more oxygen than is released into the atmosphere or is used by other organisms in the water. Thus, DO levels in water can be used as indications of high primary productivity (high levels of photosynthesis).

Dissolved oxygen concentrations, measured from 1994 to 2024, increased significantly for one station on SML (Buoy R12 on the Roanoke) and two stations upstream of SML (Blackwater at Route 812 Bridge and Gills Creek at Route 834 Bridge). The Sen's slope for these stations ranged from 0.42 to 1.26 mg L^{-1} $decade^{-1}$. The increasing DO trends could potentially reflect more primary production as described above, however, the chlorophyll-*a* data for these stations do not support this scenario. These upward trends could also suggest improving oxygen conditions, potentially reflecting enhanced water quality or reduced biological oxygen demand.

In contrast, the results for the lake station on Gills Creek showed a significant decreasing trend for DO concentrations (Sen's slope of -0.71 mg L^{-1} $decade^{-1}$). This trend could suggest less primary production, but the chlorophyll-*a* data do not support a drop in primary productivity at this location. A drop in DO levels may, instead, reflect degrading water quality or increasing biological oxygen demand.

pH: The pH scale indicates the acidity or alkalinity of waters, with values below 7 being acidic and values above 7 being alkaline. Cyanobacteria prefer neutral (pH = 7) to alkaline (pH > 7) conditions. At low pH levels, cyanobacteria must expend energy to maintain their optimal intracellular pH levels, which otherwise could interfere with metabolic processes and photosynthesis (Interstate Technology & Regulatory Council [ITRC], 2020). Thus, lower pH levels (acidic waters) can slow cyanobacterial growth.

During cyanobacterial blooms, alkaline conditions (pH > 7) typically occur within surface waters, where cyanobacteria are photosynthesizing. The process of photosynthesis requires carbon dioxide (CO_2), which when dissolved in water forms a weak acid (carbonic acid, H_2CO_3). Therefore, removing carbon dioxide from the water column for use in photosynthesis prevents the formation of carbonic acid and has the effect of raising the pH (makes it alkaline). Thus, pH measurements of surface waters can be used as indications of primary productivity, and increasing trends of pH would be expected for stations with frequent cyanobacterial blooms and increasing primary productivity over time.

Instead of seeing increasing pH trends, all stations on SML had significant downward trends in pH (Sen's slope range: -0.22 to -0.09 $decade^{-1}$ for the 1994–2024 monitoring period). Additionally, two of the four stations upstream of SML also had decreasing trends in pH: Route 812 Bridge on Blackwater (Sen's slope: -0.06 $decade^{-1}$) and Route 757 Bridge on Beaverdam

Creek (Sen's slope: -0.80 decade^{-1}). The downward trends for pH may result from increases in atmospheric carbon dioxide (CO_2) from the burning of fossil fuels (produces carbon dioxide). This carbon dioxide is released into the atmosphere and dissolves in water to form carbonic acid, with the acid lowering the pH of the water. Furthermore, although sulfur and nitrogen emissions that cause acid rain have significantly dropped, past and current depositions likely continue to impact the SML region of Virginia.

The station at the Blue Ridge Parkway Bridge, which is located just downstream of the City of Roanoke, had a significant upward trend for pH (Sen's slope: 0.19 decade^{-1}). Unfortunately, there are no chlorophyll-*a* data at this station for comparison, but the DO results for this station do not indicate an increasing trend in primary productivity. The increasing pH trend for this station is more likely reflecting urban and industrial runoff that contains alkaline substances. Sources could include runoff from cement and construction materials, as well as runoff from homes and businesses containing detergents, lawn fertilizers with lime, etc.

Total Suspended Solids: Total suspended solids (TSS) represent the solid particles like soil and debris that float in a waterbody. The TSS data in this study reflected measurements collected from 1994–2003. The TSS concentrations declined significantly at four stations on SML (dam, confluence of the Blackwater and Roanoke arms, lower Blackwater, and mouth of Bull Run) and two stations upstream of SML (Blackwater and Gills Creek). The Sen's slopes for these six stations ranged from -5.58 to -0.42 mg L^{-1} decade^{-1}. These results indicate reduced particulate loading over time, which should improve water quality.

The impact of lower TSS concentrations on cyanobacterial bloom formation is complex. Total suspended solids can serve as a source of nutrients, particularly for phosphorus, which attaches to TSS. Therefore, lower levels of TSS could negatively impact cyanobacteria if low phosphorus levels are limiting cyanobacterial growth. Conversely, high TSS levels in water block light, thereby hindering photosynthesis, and TSS can negatively impact the floating ability of cyanobacteria. Lower levels of TSS would increase light conditions to support more photosynthesis and cyanobacterial growth and would allow for more movement within the water column by cyanobacteria, which is an advantage they have over other phytoplankton (many cyanobacteria, unlike most other phytoplankton, can actively control their vertical position within the water column). Thus, reductions of TSS are a positive trend for water quality within SML, but these reductions can have a negative or positive influence on cyanobacterial bloom formations.

Discussion of Trend Results: Reducing nutrients within SML is key to managing cyanobacterial blooms. Nitrogen and phosphorus are needed by cyanobacteria in the largest quantities so are typically the nutrients that limit cyanobacterial growth. Because many cyanobacteria can fix nitrogen from the air, controlling nitrogen levels can be ineffective without also controlling phosphorus levels. Historically, lake managers have focused on phosphorus because phosphorus is typically the limiting nutrient for primary producers in freshwater systems. Some managers use a dual strategy of controlling both nitrogen and phosphorus simultaneously in an attempt to prevent cyanobacterial blooms.

Decreasing trends observed for nitrogen and phosphorus are positive signs for controlling cyanobacterial blooms within SML, but increasing chlorophyll-*a* trends are cautionary signs. Upward trends for chlorophyll-*a* were observed for stations within the main (dam) region of SML and in both the Blackwater and Roanoke arms of the lake. It seems somewhat counterintuitive that as nitrogen and phosphorus levels decrease, chlorophyll-*a* levels increase. However, if the decreasing trends in nitrogen and phosphorus are not yet yielding low enough nutrient levels to limit the growth of primary producers, increased water temperatures and other factors that favor the growth of primary producers will lead to higher levels of primary production and chlorophyll-*a*.

Also, changes in vertical mixing may be affecting the depth-distribution of nutrients within the water column. When vertical mixing is enhanced, nutrients are brought from deeper depths into the upper layer of the lake and may fuel blooms. Vertical temperature gradients in the upper reservoir have decreased in recent decades (Bukaveckas et al., 2025). Weakening temperature gradients increase the likelihood of entraining deeper, nutrient-rich layers under certain climatic conditions (e.g., elevated wind speed) or in response to vertical mixing induced by boating activity (e.g., wakeboarding).

The strongest trends observed in this study involved changes in total hardness, sulfates, chlorides, and TSS. These parameters have not been monitored in SML in more than 20 years. The DEQ monitored total hardness from 1997 to 2003, sulfate and chloride from 1994 to 2001, and TSS from 1994 to 2003. The concentrations at the monitored stations have most certainly changed since they were last monitored, and it would be useful to know their current status. Given the strong trends and influences these parameters have on cyanobacterial populations, it would be helpful to obtain more current monitoring data for total hardness, sulfates, chlorides, and TSS.

Water Quality Variable Correlations

We examined associations among water quality variables using Spearman's rank-order correlations (Helsel et al. 2020). This statistical method follows a non-parametric approach (e.g., does not require the data to be normally distributed). It performs well with outlier data and non-linear relationships. The Spearman rank-order correlation highlights monotonic associations, those relationships that consistently increase or consistently decrease.

The Spearman correlation coefficient (ρ) ranges from -1 to +1. Positive values indicate that as one variable increases, the other tends to increase, and negative values signify that as one variable increases, the other tends to decrease. The closer the coefficient is to -1 or +1, the stronger the monotonic association (consistently increasing or consistently decreasing). Values near zero (0) signify no monotonic relationship. Strong correlations only indicate strong associations between the two variables. Correlations do not imply that a change in one variable causes the change in the other.

For each station, we included key parameters, such as pH, temperature, dissolved oxygen, various nitrogen and phosphorus species, chlorophyll-*a*, TSS, and Secchi depth. We present average correlation data from water samples obtained in SML for variables exhibiting strong correlations (Table 10).

Table 10. Selected variable pairs with relatively strong correlations ($|\rho| > 0.5$) observed across multiple monitoring stations.

Variable Pair	Stations (n)	Average ρ
Total Nitrogen & NO_x	6	+0.823
DO & pH	5	+0.685
Temp & DO	4	-0.533
Temp & NO_x	4	-0.507
TSS & Secchi Depth	6	-0.632
Chloride & Sulfate	2	+0.942

Total nitrogen concentrations, which represent the organic and inorganic forms of nitrogen, and NO_x (nitrate + nitrite) concentrations show a tight coupling (6 stations; average $\rho \approx +0.82$). The coefficient value suggests a strong tendency for total nitrogen and NO_x to respond similarly. Monitoring stations with high levels of total nitrogen also tend to have high levels of NO_x, and stations with low levels of total nitrogen tend to have low levels of NO_x. This connection is logical because NO_x is a component of total nitrogen.

Dissolved oxygen also has a strong, positive association with pH (5 stations, $\rho \approx +0.69$). In waters near the surface, this association likely results from their connections to photosynthesis. Primary producers (cyanobacteria, algae, and plants) generate DO as a biproduct of photosynthesis. They also cause the pH of water to increase when photosynthesizing by utilizing carbon dioxide from the water, which lowers the acidity of the water (increases pH). Thus, more photosynthesis yields more DO and higher pH levels. In deep waters, this association is likely driven by decomposing bacteria. These bacteria take in oxygen, which lowers DO levels, and they respire carbon dioxide, which lowers the pH of the water (H_2O) when it reacts with carbon dioxide (CO_2) to form carbonic acid (H_2CO_3).

Negative correlations were observed for temperature and dissolved oxygen (4 stations; average $\rho \approx -0.53$) and for temperature and NO_x (4 stations; average $\rho \approx -0.51$). Both DO and NO_x levels within lakes are temperature dependent. As water temperatures increase, warmer water molecules move faster, which allows oxygen to escape into the atmosphere more easily. Thus, warmer waters hold less DO than colder waters. Nitrate and nitrite levels in a lake are also heavily dependent on temperature. For example, denitrifying bacteria can convert NO_x into nitrogen gas (N_2). These bacteria are more active and efficient in warmer waters so NO_x levels decrease more quickly in warm waters. Likewise, cyanobacterial and algal populations that utilize NO_x are more actively growing in warmer warmers so pull more NO_x from the water. Additionally, lake stratification physically controls the distribution of NO_x within the lake. Combined, these processes cause the detected inverse correlation between temperature and NO_x.

As expected, total suspended solids (TSS) and Secchi depth co-vary negatively (6 stations; average $\rho \approx -0.63$). Measurements of TSS record the amount of fine particles (e.g., silt, clay, algae, organic matter) that are suspended within the water and can be captured on a filter. Thus, high concentrations of TSS are associated with high levels of turbidity (e.g., murky or muddy water). Conversely, the Secchi depth measures the transparency of the water. Secchi depth is determined by lowering a disk into the lake and measuring the depth where it ceases to be visible

from the surface. Clearer waters, therefore, have higher Secchi depth measurements. As TSS concentrations decrease, Secchi depths increase, and vice versa.

Chloride and sulfate also show as a pair (2 stations; $\rho \approx +0.94$), offering that as chloride concentrations increase, sulfate concentrations also consistently increase. This association could possibly reflect a shared source (e.g., from de-icing materials, weathering rock, fertilizer, animal waste, etc.) or transport pathways (e.g., in runoff, effluent, atmospheric deposition, etc.).

When monitoring, the DEQ typically collected water samples near the surface of the lake (≈ 0.3 m) and from deeper within the water column, typically including near the bottom of the lake. Thus, we compared the correlations across depth-stratified subsets (near surface vs. deeper) and the combined dataset (described above). We found that the linkages are strong regardless of depth, and the nutrient pair correlations were even higher for the data from deeper samples. Overall, the "big-picture" relationships remain the same as when data from all depths are combined.

SML Water Quality Monitoring Program Data

We complemented the SML water quality data obtained from DEQ with data obtained through the SML Water Quality Monitoring Program. Here, we have summarized our findings. The complete report is available from the Virginia Water Resources Research Center (E-mail: water@vt.edu).

The SML Water Quality Monitoring Program operates through a collaborative effort between scientists and student technicians from Ferrum College and trained volunteers with the SMLA. The program has been collecting and recording data from the lake since 1987.

The monitoring season for the SML Water Quality Monitoring Program begins towards the end of May and ends during the first or second week of August. The program analyses various water quality parameters at established stations every other week throughout the monitoring period for a total of six samples collected at each station during the monitoring season.

Each year, scientists from Ferrum College develop an annual report that summarizes the findings from that monitoring season and compares it to previous seasons. We examined long-term trends for the following data obtained by the SML Water Quality Monitoring Program:

- Total phosphorus (TP) concentrations from 19 tributary stations;
- Chlorophyll-*a* (Chl-*a*) and TP concentrations along with Secchi disc depths used to estimate a trophic state index (TSI) from 56 stations in the lake;
- Phytoplankton abundance at 19 lake stations (14 from horizontal tows, and 5 from vertical tows); and
- Temperature, dissolved oxygen (DO), pH and conductivity from five depth-profile stations within the lake.

Tributary Phosphorus Loads

We estimated annual loads of phosphorus into SML from tributary TP concentration data (from the 2002–2024 annual reports by Ferrum College) and average daily flows (as estimated by the SWAT model; Table 11). The TP loads derived from these data can be helpful in identifying tributaries with higher phosphorus loading, but we note their uncertainty for other applications (e.g., TMDL development) given the streamflow data are model estimates and variability within the TP data.

On the Blackwater arm, the headwater station (T3) carries the highest load of TP (≈126 lbs/day). Maggodee Creek (T1a) has the next highest load of TP (≈35 lbs/day), followed by Gills Creek (T2a: ≈ 25 lbs/day). Stations T4–T8 on the Blackwater contribute comparatively much smaller amounts of phosphorus to SML (≤1.3 lbs/day).

The largest load of phosphorus to SML, by far, comes from the Roanoke River, which has the highest flow. The Roanoke River has two stations in proximity, but their phosphorus concentrations are quite different, yielding substantially different loads (T17: ≈236 lbs/day; T21a: ≈396 lbs/day). Beaver Dam Creek (T16) carries an estimated TP load of approximately 11 lbs/day, and all other stations on the Roanoke arm carry much lower loads. Five monitored tributaries to the Roanoke arm are very small, which prevented us from using the SWAT model to calculate average daily flows for them. For these tributaries, we used the smallest average flow in the dataset (T6, Bull Run) to estimate loads and recognize that the actual loads should be smaller than the estimated loads.

Table 11. Tributary stations to the Blackwater and Roanoke arms of SML, along with their average daily flow (cms, cubic meters per second), total phosphorus concentrations (µg/L) and loads (pounds/day) during the monitoring season (end of May to mid-August) from 2002-2024.

	Station Name	Description	Latitude	Longitude	Average daily flow (5/27-8/11) (cms)	Average TP Conc. (µg/L)	Average TP Load (lbs/day)
Blackwater Arm							
T0a	Gills Creek	At Rt 122	37.1253	-79.7825	0.6338	108.0	13.0
T1a	Maggodee Creek	At dam at end of Rt. 871	37.0559	-79.8303	1.6447	112.8	35.3
T2a	Gills Creek	At Rt. 833 bridge	37.0797	-79.7023	1.1312	115.9	25.0
T3	Blackwater	At Rt. 834 bridge	37.0558	-79.7596	6.4364	102.4	125.6
T4	Poplar Camp Creek	At Rt. 839 bridge	37.0251	-79.7482	0.1094	42.5	0.9
T5	Standiford Creek	At Rt. 938 bridge	37.0137	-79.6969	0.1377	51.4	1.3
T6	Bull Run	At culvert under Rt. 647	36.9962	-79.6580	0.0989	53.2	1.0
T7*	Cool Branch	Off Rt. 626	37.0128	-79.5874	<0.1062	23.9	< 0.5
T8	Lumpkins Marina Creek	Off Rt. 626	37.0144	-79.5888	0.1062	33.5	0.7
Roanoke Arm							
T12†	Surrey Drive	At culvert	37.0929	-79.5798	< 0.0989	38.3	< 0.7
T13†	Snug Harbor	Harbor Trail/ Spinnaker Way	37.1513	-79.6462	< 0.0989	30.5	< 0.7
T14†	Stoney Creek	At culvert on Gap Bridge Rd.	37.1730	-79.6903	< 0.0989	164.4	< 3.1
T15	Jumping Run	Off Rt. 653	37.2049	-79.7098	0.1192	107.9	2.5
T16	Beaver Dam Creek	Fishermans Cove Rd. bridge	37.2248	-79.7503	0.6448	92.0	11.3
T17	Bay Rock Marina	Off gas dock at marina	37.2197	-79.7973	15.9991	77.5	236.2
T18	Lynville Creek	At Rt. 634 bridge	37.1961	-79.7828	0.2302	65.7	2.9
T19a†	Grimes Creek	At Wooded Acres Drive	37.1680	-79.7291	< 0.0989	92.0	< 1.7
T20†	Indian Creek	At culvert, Rt. 636	37.1400	-79.7505	< 0.0989	72.8	< 1.4
T21a	Roanoke River	Near Lakeshore Terrace Rd.	37.2227	-79.8144	15.9747	130.1	395.9

* Used flow from nearby Lumpkins Marina Creek (T8) to estimate load.

† Used lowest flow from dataset (T6, Bull Run) to estimate load.

Lake Trophic Data

We received a dataset with 23 years (2002–2024) of data for 56 stations across SML from the SML Water Quality Monitoring Program. The dataset included measurements for the following:

- Secchi depth (measures transparency), which is reduced by primary production;
- Concentrations of TP, which indicate the potential for algal and cyanobacteria growth;
- Concentrations of Chl-*a* (found in primary producers), which correlate to higher levels of primary production; and
- Trophic State Index (TSI) values based on the Chl-*a* data; used to classify the lake according to its productivity.

We calculated averages for Secchi depth, TP, and Chl-*a* for each of the 56 stations. There was a longitudinal gradient for these data. In general, stations near the dam had higher transparencies and lower TP concentrations than those located upstream. The lowest Chl-*a* values were found near the dam, and higher values progressed upstream. The Roanoke arm had two spikes in Chl-*a* concentrations. The first, and smaller spike, corresponded to where the flow slows to make a series of sharp turns. A larger spike in Chl-*a* concentrations was approximately 25 miles from the dam, and the most upstream stations on the Roanoke arm had somewhat lower Chl-*a* concentrations. In the Blackwater arm, the most upstream stations had the highest Chl-*a* concentrations.

Lakes with values for TSI below 40 are considered oligotrophic and are characterized by waters with low nutrient levels and algal productivity. Sixteen stations on SML had TSI scores below 40. These stations were all within 10 miles of the dam. Values for TSI greater than 50 indicate eutrophic conditions, with eutrophic lakes having nutrient-rich waters with high levels of algal productivity. Fifteen stations on SML could be classified as eutrophic based on this dataset. The stations reflecting eutrophic conditions were 20 or more miles from the dam. The overall lake TSI was 45, indicating the lake is mesotrophic (having moderate levels of nutrients).

Cyanobacteria Data

We obtained phytoplankton data from the SML Water Quality Monitoring Program for 2010 to 2023. They estimated phytoplankton abundances from five 10-m vertical tows and fourteen 10-m horizontal tows collected from throughout the lake. We used the reported counts per milliliter of sample, took into account the amount of water sampled by the tow, and expressed the abundance of phytoplankton in organisms per milliliter of lake water as reported in annual reports authored by the scientists at Ferrum College.

We calculated average and median (the midpoint of a ranked data set) cyanobacteria counts (organisms per mL) for each of the 19 monitoring stations on SML. The headwater station on the Roanoke River (station 1) had the lowest cyanobacteria levels, and stations near the dam also tended to have lower levels of cyanobacteria compared to other stations on SML. By far, the station 13 miles from the dam on the Blackwater arm (PB13) had the highest levels of cyanobacteria. From this dataset, we were able to see which stations were impacted by the 2023 blooms. They included stations on the Blackwater arm and Gills Creek, the station at the confluence of the Roanoke and Blackwater arms (10), a station on the lower Roanoke arm (PR11), and the monitoring station closest to the dam (PM2).

We considered all datapoints for cyanobacteria with higher than 7 organisms/mL, which is above the average for most stations and suggests a strong population. This level should not be taken to indicate a bloom condition but simply provides a means to describe the cyanobacteria populations within SML. Six groups of cyanobacteria were found to exceed 7 organisms/mL in samples from SML: *Anabaena/Nostoc* (considered together), *Aphanizomenon*, *Aphanocapsa*, *Microcystis*, *Planktothrix* (formerly *Oscillatoria*), and *Phormidium*. All, except *Aphanocapsa*, were on the PTOX 2024 list by VDH. This dataset suggests that in SML, co-domination of cyanobacteria genera is possible, but typically, one genus dominates at a time in each location.

- *Anabaena/Nostoc* are common throughout SML. These two genera are often classified together because both are filamentous cyanobacteria that share many characteristics and can be difficult to differentiate. Stations PB13 and 12 on the Blackwater arm had the highest averages of these nitrogen-fixing genera. Note: many species identified as *Anabaena* in the past now belong to the genus *Dolichospermum*. We use *Anabaena* because the Ferrum College lab does not base its counts on the presence or absence of gas vacuoles, which is how *Anabaena* and *Dolichospermum* are distinguished. Also, the Ferrum scientists have found *Anabaena circinalis* to dominate in SML.
- *Aphanizomenon* was only monitored by the Ferrum College Water Quality Lab beginning in monitoring period two of 2023. This nitrogen-fixing genus dominated the 2023 blooms in SML. As expected, the highest levels of *Aphanizomenon* were from stations on the Blackwater arm and Gills Creek.
- *Aphanocapsa*, a non-nitrogen fixing genus of cyanobacteria, was only found at one station (station 12 on the lower Blackwater arm) on one occasion (in 2013) where it exceeded 7 organisms/mL.
- *Microcystis*, another non-nitrogen fixing cyanobacteria, only occurred at levels exceeding 7 organisms/mL on two occasions. Once in the upper Roanoke (station 2) in 2012, and once in the upper Blackwater (station 14) in 2022.
- *Planktothrix* (formerly *Oscillatoria)* was found to primarily exceed 7 organisms/mL in SML in 2016. It was identified on the Blackwater (PB13), Gills Creek (13), and at most stations on the Roanoke (8 of 9 Roanoke stations) at levels exceeding 7 organisms/mL. Not surprisingly, the genus was found first in the vertical tows. *Planktothrix* is known to inhabit the metalimnion, the region between the warmer surface waters (epilimnion) and the colder, deeper waters (hypolimnion).
- *Phormidium* exceeded 7 organisms/mL most often in both vertical and horizontal tows collected by the SML Water Quality Monitoring Program. It was found to exceed this level in nine of the 14 monitoring seasons that were analyzed and at all stations except station 1 in the upper Roanoke (which never exceeded 7 organisms/mL for any genus). Although common throughout the monitoring seasons, the abundance levels for *Phormidium* were not as high as observed for the other common genera (*Anabaena/Nostoc*, *Aphanizomenon*, and *Planktothrix*).

Depth Profile Data

The SML Water Quality Program has been collecting depth profile data at five stations on SML since 2005. We summarized the main profile findings reported in the 2005–2024 annual reports developed by Ferrum College. The profile data reflect the biological and chemical processes occurring within SML. Within SML, the depth-profile data at stations typically exhibited the following characteristics:

(1) Temperature
   a. Thermal stratification had formed within the lake prior to the first measurements being taken in late May or early June.
   b. The thermocline was located approximately 4–10 meters from the surface.
   c. Lake temperatures increased steadily from the first to sixth profiling date, such that August temperatures were consistently higher than late May/early June temperatures.

(2) Dissolved Oxygen
   a. High levels of DO were found in the upper layer (epilimnion) throughout the monitoring season.
   b. Decreasing DO concentrations were seen below the thermocline throughout the monitoring season.
   c. Anoxic (depleted of DO) bottom waters appeared in June for the most upstream station on the Roanoke (PR19) and by the end of July for all stations.

(3) pH:
   a. The pH values were higher in the epilimnion and lower in the hypolimnion, as expected for a stratified lake.
   b. All pH-depth profiles showed alkaline (pH > 7) conditions in the epilimnion (often ≈ 8.5) during the day (when profile data were collected).
   c. Stations furthest from the dam (i.e., PB13 and PR19) had higher surface pH values, frequently above 8.5.
   d. In the hypolimnion, pH conditions quickly decreased to approximately 7.0.
   e. Hypolimnion pH values tended to decrease from early summer to late summer as carbon dioxide accumulated, making the water more acidic (pH < 7).

(4) Conductivity:
   a. The Roanoke arm (PR11 and PR19) consistently had higher electrical conductance levels than the Blackwater arm (PB7 and PB13) indicating higher dissolved solids.

In 2023, stations PB7 and PB13 on the Blackwater were most impacted (of the profile stations) by the blooms. We examined shifts in the DO, pH, and electrical conductance measurements from one monitoring period to the next as these two stations reflected changes from the growth and collapse of cyanobacterial blooms.

- Higher DO concentrations in the epilimnion indicated more primary production at PB13 compared to PB7, as supported by the cyanobacteria abundance data.
- The pH values for PB7 were more stable than those for PB13, suggesting that station PB7 was less affected by cyanobacterial blooms in 2023 compared to PB13 (and confirmed by the phytoplankton data).
- The pH data exhibited a lag in response from the initial increase in cyanobacterial abundance to the peak pH values, suggesting that it takes time for a significant buildup of cyanobacteria biomass to consume enough carbon dioxide (CO_2) to cause the pH to rise.
- The pH measurements at station PB13 provide evidence of decomposition occurring at the surface of the water on May 30, 2023 and June 27, 2023. The comparatively lower pH readings could have resulted from respiration by bacteria involved in decomposition of dead and dying cyanobacteria that can accumulate on the water surface during a bloom.

- On June 27, 2023 (peak of blooms as indicated by this dataset), the depth-profile DO values for PB13 suggested decomposition was occurring at the thermocline, and the pH changes at the thermocline on this day supported this finding.
- The highest epilimnion DO levels at PB7 and PB13 for the monitoring season were recorded on August 8, 2023, once the cyanobacterial blooms had ended. This finding may be the result of wind (mixing the water with air) and/or may have occurred as a result of decreased cyanobacteria decomposition in the epilimnion (which had occurred during the blooms) and increased water clarity, which increased the photic zone to allow for more photosynthesis (and more DO generation) in the epilimnion. Additionally, other photosynthesizing phytoplankton likely began to increase in population in the epilimnion following the collapse of the cyanobacterial blooms.

In conclusion, the profile data obtained by the SML Water Quality Monitoring Program provide a glimpse into the processes occurring within SML. Pairing these data with phytoplankton data obtained at the same time and location can help to identify conditions favorable for cyanobacterial blooms and to allow for comparisons that shed light on how the growth and decline of cyanobacteria populations impact the conditions of the lake.

Objective 2, Task 2: Land-Use Analysis

NLCD Land Use and Cover Change (2001-2023)

We assessed land cover change between 2001 and 2023, with a focus on urban expansion and key transition classes in the SML watershed, as well as the Blackwater and Roanoke River basins separately. Using the National Land Cover Dataset (NLCD) from 2001 and 2023, we quantified developed (urban) land areas for two analytical units: watershed-level (basins) and lake/stream buffers (500 m and 1 km) surrounding SML. Tables 12 and 13 show the general land-cover distributions at both scales using NLCD data from 2001 as the baseline.

Table 12. General land-cover distribution for Blackwater River Basin and Roanoke River Basin.

Blackwater River Basin		
	Area (km^2)	Percent
Developed/urban	57.8	8.3
Ag	201.0	28.7
Forest	410.3	58.7
Other	30.4	4.4
Total	699.4	100
Roanoke River Basin		
	Area (km^2)	Percent
Developed/urban	399.6	21.2
Ag	250.6	13.3
Forest	1172.1	62.2
Other	60.9	3.2
Total	1883.1	100

Table 13. General land-cover distribution within 500 m and 1 km buffer zones of the Blackwater and Roanoke River Basins.

Blackwater River Basin				
	500 m buffer		**1 km buffer**	
	Area (km^2)	Percent	Area (km^2)	Percent
Developed/urban	11.6	14.0	13.9	12.7
Ag	12.1	14.6	21.7	19.8
Forest	33.3	40.1	47.6	43.5
Other	26.0	31.3	26.4	24.1
Total	83.0	100	109.5	100
Roanoke River Basin				
	Area (km^2)	Percent	Area (km^2)	Percent
Developed/urban	20.9	15.3	26.5	14.6
Ag	10.9	8.0	21.2	11.7
Forest	59.5	43.6	88.2	48.6
Other	45.1	33.1	45.7	25.2
Total	136.5	100	181.5	100

At the basin (watershed) level, urban area in the Blackwater River Basin increased from 57.75 km² in 2001 to 68.43 km² in 2023, an 18.5% increase (Table 14). In the Roanoke River Basin, urban area expanded from 399.61 km² to 439.31 km² over the same period, representing a 9.9% growth. Collectively, these two basins experienced an 11.0% increase in urban area over two decades. Within the SML buffer zones, urban expansion was even more pronounced. The 500 m buffer saw a 29.3% increase in urban areas, while the 1 km buffer expanded by 27.2%, indicating more intense localized development near the lake (Table 15).

Table 14. Urban Area Change Summary (km²): Basin-level summary.

	Blackwater River Basin	Roanoke River Basin	Total (km^2)
Developed/urban 2001	57.75	399.61	457.36
Developed/urban 2023	68.43	439.31	507.74
Urban growth 2001-2023 (%)	18.49	9.93	11.02

Table 15. Urban **Area** Change Summary (km²): Smith Mountain Lake Buffer Zone summary.

	SML 500 m Buffer	SML 1 km Buffer
Developed/urban 2001	34.00	42.11
Developed/urban 2023	43.96	53.59
Urban growth 2001-2023 (%)	29.30	27.24

When examining buffer zones specific to each river basin, the Roanoke River Basin exhibited more substantial urban growth near the shoreline compared to the Blackwater Basin (Tables 16

and 17). Buffer zones at 500 m and 1 km in the Blackwater Basin experienced increases of 28.5% and 26.1%, respectively. In the Roanoke Basin, urban areas within the 500 m buffer increased by 26.7%, from 20.90 km² in 2001 to 26.49 km² in 2023. Urban area in the 1 km buffer grew by 26.9%, reaching 33.57 km².

Table 16. Urban Area Change Summary (km²): Blackwater Basin Buffer Zone summary.

	500 m Buffer	1 km Buffer
Developed/urban 2001	11.58	13.86
Developed/urban 2023	14.88	17.48
Urban growth 2001-2023 (%)	28.50	26.11

Table 17. Urban Area Change Summary (km²): Roanoke River Basin Buffer Zone summary.

	500 m Buffer	1 km Buffer
Developed/urban 2001	20.90	26.46
Developed/urban 2023	26.49	33.57
Urban growth 2001-2023 (%)	26.70	26.87

The most prominent land cover transitions involved shifts from forest and agricultural areas to urban land. Within the basin, forest-to-urban conversion totaled 32.63 km², while agriculture-to-urban conversion contributed an additional 18.79 km² (Table 18). Notably, a significant area (14.15 km²) also transitioned from forest to agriculture. Around SML, the 1 km buffer experienced 4.27 km² of forest-to-urban conversion and 6.49 km² of agriculture-to-urban change, further confirming pressure from urban development near the lake (Table 19). Tables 20 and 21 summarize land cover transitions within the buffer zones for each river basin.

Table 18. Main Classes of Land Cover Change (km²): Basin-level summary.

	Blackwater River Basin	Roanoke River Basin	Total (km^2)
Forest->Urban	6.94	25.69	32.63
Ag->Urban	3.81	14.98	18.79
Forest->Ag	7.15	7	14.15

Table 19. Main Classes of Land Cover Change (km²): Smith Mountain Lake Buffer Zone summary.

	SML 500 m Buffer	SML 1 km Buffer
Forest->Urban	3.21	4.27
Ag->Urban	5.95	6.49
Forest->Ag	1.68	2.77

Table 20. Main Classes of Land Cover Change (km²): Blackwater River Basin Buffer Zone summary.

	SML 500 m Buffer	SML 1 km Buffer
Forest->Urban	1.34	1.59
Ag->Urban	1.75	1.84
Forest->Ag	0.80	1.26

Table 21. Main Classes of Land Cover Change (km²): Roanoke River Basin Buffer Zone summary.

	SML 500 m Buffer	SML 1 km Buffer
Forest->Urban	1.68	2.47
Ag->Urban	3.75	4.19
Forest->Ag	0.80	1.42

VGIN High-Resolution Land Cover

The Virginia Geographic Information Network (VGIN) 2016 data set provides land cover at a much higher resolution (1 m) compared to NLCD (30 m). As such, we used the VGIN to further assess the distribution of land cover classes around SML. These classes are open water, impervious surface, barren land, forest, tree, shrub/scrub, harvested/disturbed forest, turf grass, pasture, cropland, National Wetlands Inventory (NWI) wetlands, and other lands. While the classification definitions of forest and tree classes are slightly different, they are combined for this summary. Furthermore, only the most abundant land cover classes are summarized below.

Analysis was conducted for buffers set at 500 m and 1 km surrounding the entirety of SML and separately for the Blackwater and Roanoke arms. Within 500 m of SML, the majority class is forest/tree (hereafter referred to as forest). The total forested area is 118 km^2, comprising 49% of the total zone area (243 km^2; Table 22). The next most abundant classes within the SML buffer zone are turf grass, pasture, and impervious, at 6.4%, 6.3%, and 5.5%, respectively.

Within 1 km of SML, forest is also the dominant class, at 174 km^2, making up 53.6% of the total zone area (324 km^2). The next most abundant classes are consistent in the 1 km buffer, with pasture, turf grass, and impervious surfaces covering 9%, 6.2%, and 4.8% of the SML buffer zonal area, respectively. Tables 23 and 24 further summarize buffer land covers for each river basin.

Table 22. Land Cover Summary (km^2): SML Buffer Zone summary.

	SML 500 m Buffer	SML 1 km Buffer
Forest	118.45	173.58
Turf Grass	15.52	20.19
Pasture	15.39	29.24
Impervious Surface	13.29	15.66

Table 23. Land Cover Summary (km^2): Blackwater Buffer Zone summary.

	Blackwater 500 m Buffer	Blackwater 1 km Buffer
Forest	40.22	57.78
Turf Grass	8.79	10.14
Pasture	6.53	7.91
Impervious Surface	4.11	4.73

Table 24. Land Cover Summary (km^2): Roanoke Buffer Zone summary.

	Roanoke 500 m Buffer	Roanoke 1 km Buffer
Forest	68.11	99.84
Turf Grass	5.92	5.92
Pasture	8.12	11.30
Impervious Surface	8.16	9.83

Objective 2, Task 3: Watershed Modeling

Here, we focus on potential nutrient and sediment mass inputs into SML from non-point sources, which are a result of modeled stream flows into the lake and their associated nutrient concentrations. Although some stream flow and water quality data can be obtained from U.S. Geological Survey (USGS) gauge stations, such data did not provide sufficient spatial or temporal coverage. For instance, monitoring data might only be available for a subbasin outlet or for a short period. To address this limitation, we used the Soil and Water Assessment Tool (SWAT) to establish boundary conditions regarding nutrient and sediment loads from non-point sources into SML from the major tributaries and their respective watersheds.

The SWAT model is a physically based watershed model developed by the Agricultural Research Service (ARS) of the U.S. Department of Agriculture (USDA) and has been extensively validated in agro-ecosystems (Arnold et al., 1998). This model is well-suited for watersheds with complex land uses and can be used to assess the impact of land management practices on water quality and develop TMDLs (Borah et al., 2006; Gassman et al., 2010). Also, SWAT can simulate at daily time steps and can model multiple subbasins within a watershed, providing high-resolution outputs.

The SWAT model uses key input data, such as weather (e.g., precipitation, temperature), soil, and land use data. The model uses these data to simulate hydrological processes, assess water resource availability, and predict the impact of land use changes and management practices on water quantity and quality. Management practices were not included in this simulation due to the lack of data on location and implementation, e.g., BMPs associated with animal feeding operations or urban runoff. Furthermore, given the time constraints of this study, we did not include point sources in the model even though we recognize the impact of point sources on SML is important for management purposes. Instead, the model output provides estimates for

non-point sources only. The SWAT model development process for this project is described in Appendix E.

This study applied SWAT to simulate hydrologic and water quality processes in the two major tributaries of SML: the Blackwater River Basin and Roanoke River Basin. The model was used to assess sediment, total nitrogen (TN), and total phosphorus (TP) loads from individual subbasins under current land-use and climatic conditions. We also conducted a scenario simulation to assess potential changes in nutrient loading when stream buffers are implemented in the Blackwater River Basin.

Model Area

The combined SML watershed covers approximately 2,585 km², of which the Blackwater River Basin occupies 703 km² and the Roanoke River Basin covers 1,882 km² (Figure 8a, b). Elevations in the watershed span from about 237 m at the lake area to 1,196 m on the upper ridges. Land cover information for the model was obtained from the 2011 NLCD dataset; we used this year as it was the mid-point of our simulation window (2001-2024). Land uses in the Blackwater River Basin were primarily forested areas, agriculture and low-density rural residences (Figure 9a). The Roanoke River Basin includes the Roanoke urban area, with a heterogeneous land-use mosaic of urban and suburban development, with agricultural lands and forested areas (Figure 9b). Each basin was divided into its subbasins, resulting in 17 subbasins for the Blackwater Basin and 10 subbasins for the Roanoke River Basin (Figure 10a, b).

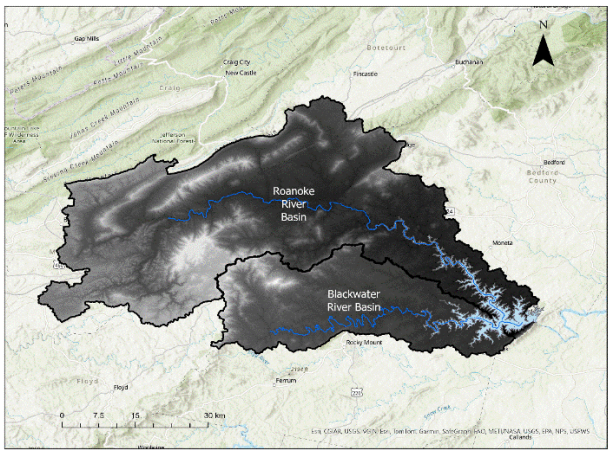

Figure 8a. Blackwater River Basin and Roanoke River Basin.

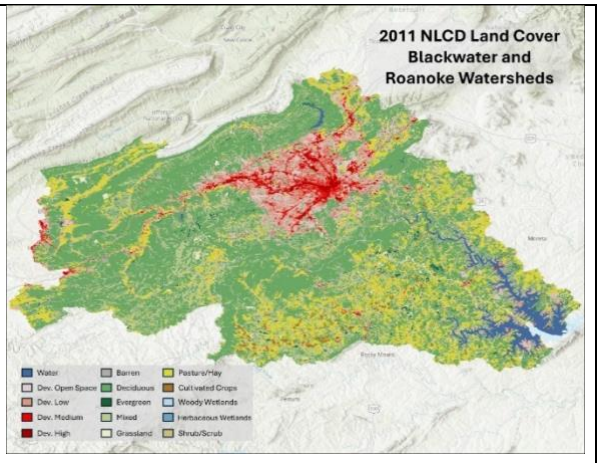

Figure 8b. NLCD land cover map (2011) for the SML watershed.

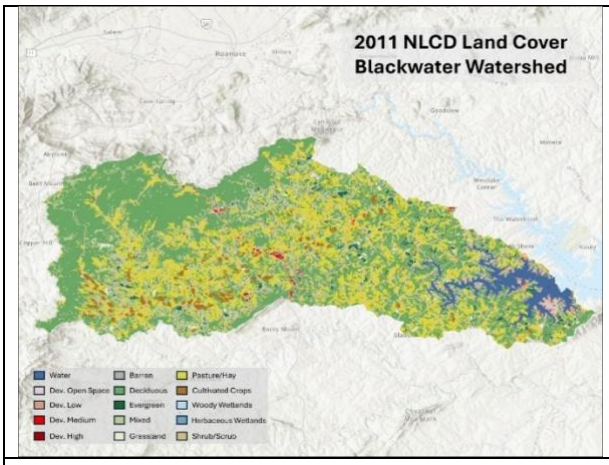

Figure 9a. NLCD land cover map (2011) for the Blackwater River Basin.

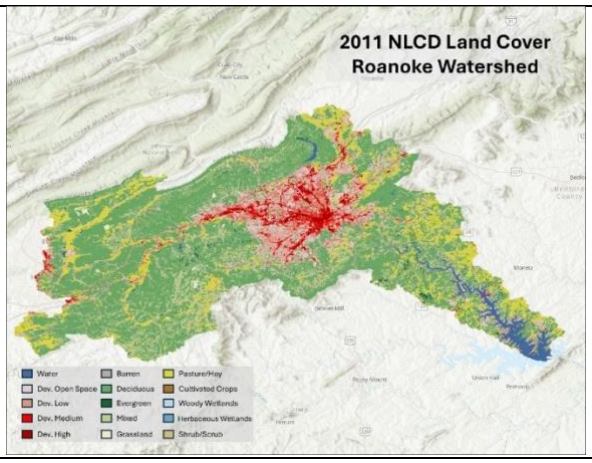

Figure 9b. NLCD land cover map (2011) for the Roanoke River Basin.

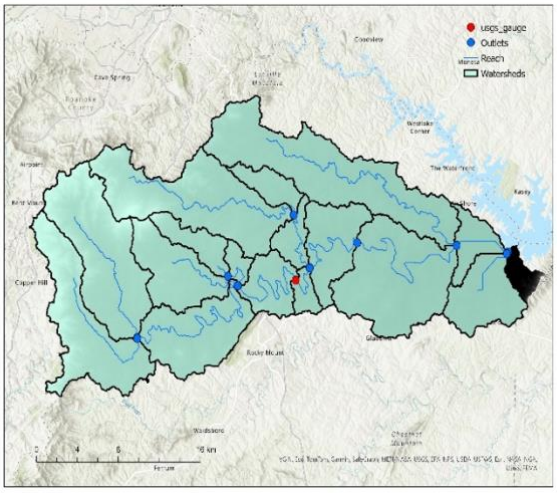

Figure 10a. Subbasins of Blackwater River.

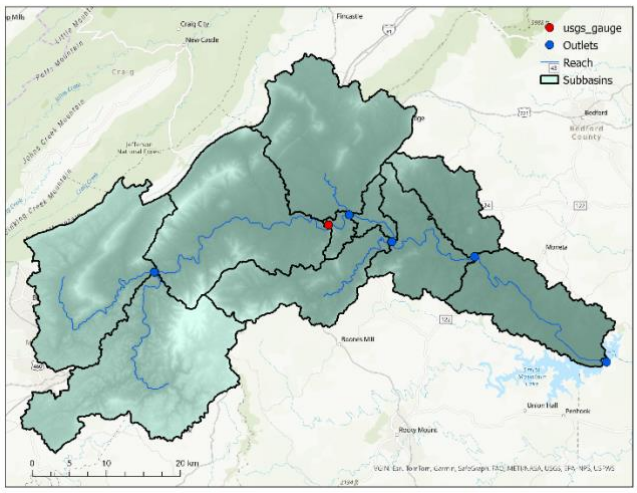

Figure 10b. Subbasins of Roanoke River.

Subbasin-Level Estimation of Sediment, Total Nitrogen, and Total Phosphorus

Due to the absence of long-term observed water quality data at inflow locations to the lake, the SWAT model was used with default parameter settings rather than calibrated parameters to estimate average annual yields of sediment, total nitrogen (TN), and total phosphorus (TP) over the simulation period 2001–2024. The SWAT outputs were analyzed at the subbasin level for both the Blackwater and Roanoke River Basins. These results highlight how land use, slope, soil characteristics, and hydrologic flow paths influence localized nutrient and sediment export patterns.

Figure 11 shows the spatial distribution of average annual nutrient and sediment yields at the subbasin scale for both the Blackwater (top row) and Roanoke (bottom row) River Basins. In each panel, color ramps are held constant across basins to facilitate direct comparison. The highest annual total nitrogen (TN, kg ha^{-1}) export in the Blackwater Basin occurs in the higher-elevation, more agricultural subbasins, whereas the Roanoke River Basin exhibits its peak TN

yields in steeper headwater subbasins draining urban landscapes. Annual total phosphorus (TP, kg ha^{-1}) closely mirror TN, with elevated phosphorus inputs concentrated in the same intensive-land-use subbasins, highlighting areas most vulnerable to contributing nutrients that feed cyanobacterial blooms. Annual sediment yield (t ha^{-1}) is highest in the steeper, upland subbasins, indicating those areas contribute disproportionately to downstream turbidity. Together, these maps underscore how differences in topography, soil erodibility, and land cover drive localized "hot spots" of nutrient export from non-point sources, which can be prioritized for targeted BMPs. Although BMPs may already exist throughout these subbasins, they were excluded from the model due to insufficient data on their local implementation.

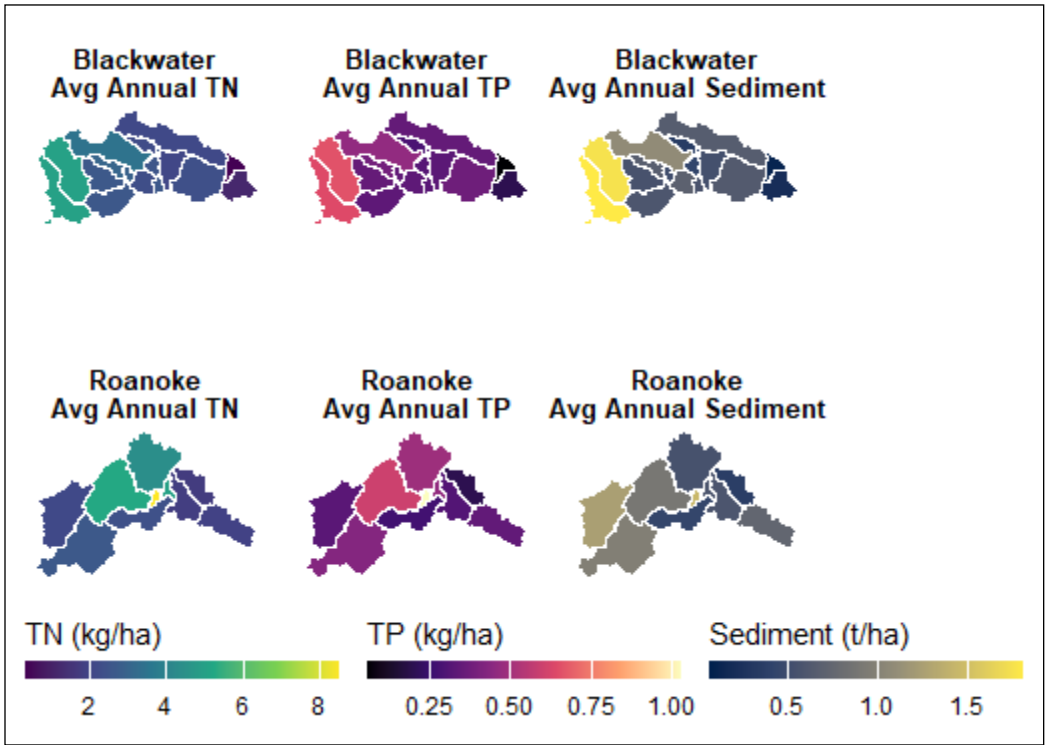

Figure 11. Subbasin-Level Estimation of Sediment, Total Nitrogen (TN), and Total Phosphorus (TP).

Scenario Simulations for Stream Buffer Implementations

We also used the SWAT model to simulate the effects of implementing a 30-m forest buffer along stream reaches, focusing on the Blackwater River basin. Through land cover reclassification and the application of filter strip management in ArcSWAT, all non-forest land cover types (e.g., pasture, cultivated land) within the buffer zone were replaced with mixed forest (NLCD code 43). Model outputs before and after this intervention were compared to evaluate average annual changes in nutrient (total nitrogen and total phosphorus) and sediment yields at the subbasin scale.

Figure 12 presents maps of absolute reductions in total nitrogen (TN), total phosphorus (TP), and total sediment across subbasins following the implementation of the 30-m forest buffer in the Blackwater watershed. The figure highlights substantial spatial variation in the effectiveness of

the buffer strips due to other local influences such as topography and soils. Absolute reductions in TN ranged from 0.05 to 1.17 kg/ha/year, with TP reductions reaching up to 0.23 kg/ha/year and sediment reductions as high as 0.16 tons/ha/year. Subbasins with higher agricultural intensity generally exhibited larger reductions in all three pollutants.

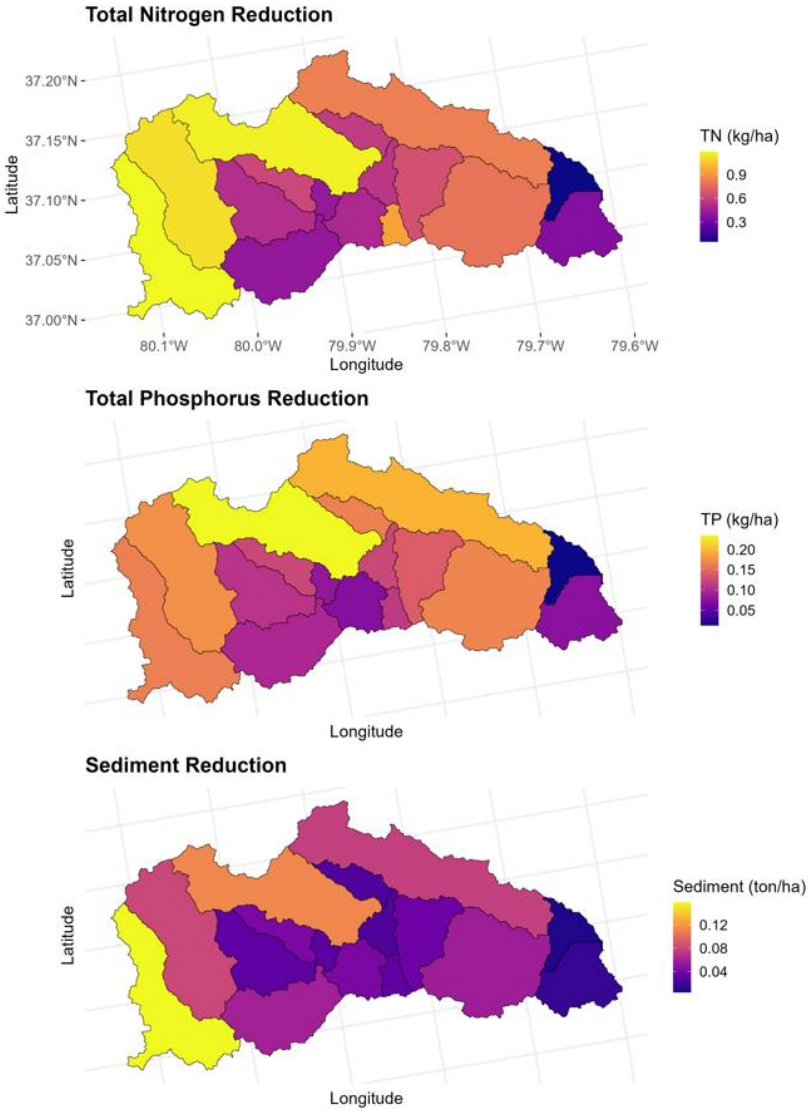

Figure 12. Model reductions from 30-meter forest buffers in total nitrogen, total phosphorus, and total sediment within subbasins of the Blackwater River.

These absolute changes correspond to percentage reductions ranging from 15% to nearly 40% for TN, and up to 58% for TP in some areas. Sediment reductions, while more modest in percentage terms, generally under 10%, still represent meaningful decreases in annual export. These results demonstrate the effectiveness of riparian forest buffers as a potential best management practice and underscore the value of spatially targeted implementation based on landscape characteristics (e.g., upslope topography, land cover, and soils).

Objective 3: Identify general management and monitoring approaches to prevent and/or mitigate HABs by considering short-term and long-term strategies and practices

The Governor and General Assembly requested that we provide recommendations for prevention of further HAB occurrences within SML. Here, we present various management options to consider for nutrient and bloom reduction strategies, along with guidance for future monitoring and research efforts.

Managing Point and Non-point Nutrient Sources

Specific management options for SML need to consider current point and non-point sources of pollution to both SML and its tributaries. This information can help guide where management efforts are most needed.

Point Sources

Since 2000, Smith Mountain Lake has been designated as a No Discharge Zone (NDZ), meaning that the discharge of treated or untreated sewage from vessels is prohibited in accordance with Virginia law. Furthermore, SML is designated as a public water supply and must meet state water quality standards accordingly. Thus, we are not aware of any direct discharges into SML.

A review of U.S. EPA's "How's My Waterway?" website (https://mywaterway.epa.gov/) for tributaries to SML (in April 2025) showed numerous permitted discharges into SML tributaries (Table 25). Peters Creek-Roanoke River has the most permits.

Table 25. Number of permitted discharges into tributaries to Smith Mountain Lake, as listed in U.S. EPA's "How's My Waterway?" (April 2025).

	Construction Stormwater	Industrial Stormwater	POTW	Pretreatment	Urban Stormwater (Small MS4)	Components Not Specified
Craddock Creek	1					
Blackwater Arm						
Bull Run	1					
Gills Creek	3		1 (elementary school only)			
Standiford Creek	2	2				
Roanoke Arm						
Bettys Creek	5					
Stony Creek	4					2
Lynville Creek	1	1				2
Peters Creek-Roanoke River	53	15	1	1	2	6

POTW = Publicly Owned Treatment Works; MS4 = Municipal Separate Storm Sewer System.

Of most interest for this study is the Roanoke Regional Water Pollution Control Plant, which treats approximately 37-million gallons of sewage each day and discharges approximately 9 miles upstream of SML. From 2020–2024, the median annual load of TKN discharged into the Roanoke River from the treated wastewater was 123,065 lbs/year, and the median load of total phosphorus from the plant's effluent into the Roanoke River was 6,573 lbs/year.

The DEQ's Water Quality Improvement Fund (WQIF) program provides grants for wastewater treatment plants in the Chesapeake Bay watershed to incentivize reducing nitrogen and phosphorus pollution, while also reducing costs for ratepayers. While WQIF grants offered by DEQ are unavailable to the Roanoke plant because it lies outside the Chesapeake Bay watershed, DEQ can provide low-cost financing through its statewide Clean Water Revolving Loan Fund program. In the Roanoke Valley, this may mean that rate users must pay for any upgrades to the system. In the past 20 years, the Roanoke Regional Water Pollution Control Plant has made several important upgrades, including improvements to reduce the possibility of sewer overflows and installation of pumps to prevent flooding of the plant during high flow events, but they have not fully updated their tertiary treatment process for nutrients. It would be a benefit to SML if funds were made available to Roanoke's wastewater treatment plant to overhaul their treatment process.

In the Blackwater River watershed, there are five farms that have Virginia Pollution Abatement (VPA) General Permits for animal waste. In the Pigg River watershed, which can impact SML through the operation of the dam's pumped-storage system, there are three more. These permits cover animal feeding operations (AFOs) with more than 300 animal units that handle liquid manure. Facilities with these permits must implement a nutrient management plan (NMP) developed by a certified planner and approved by the Department of Conservation and Recreation (DCR). Animal waste can be land-applied, but it must be done according to the approved NMP and within specific guidelines, including no application within buffer zones. In addition, facility owners and operators must complete training programs related to animal waste management and keep various records related to the management of animal waste.

Non-Point Sources

Here, we focus on strategies to help control non-point nutrient sources to the lake, such as failing septic systems and overfertilized yards located on SML. Managing such sources, may require changes in behavior by individuals. In some instances, a change in perspective may be needed as well. For example, many find lawns up to the water's edge to be aesthetically appealing; and it may require a change in perception to appreciate a taller, deep rooted, lakeshore vegetative buffer.

<u>Pay-for-Outcomes Nonpoint Source Pollution Reduction Grant Program</u>
In 2024, DEQ established a one-year grant program within the Chesapeake Bay watershed to fund projects according to the amount of nitrogen and/or phosphorus removed or prevented (instead of reimbursing implementation costs). The goal was to identify cost-effective means of reducing nonpoint source pollution and encourage innovation. Individuals, businesses, nonprofits, and government entities were eligible to receive grants ranging from $100,000 to $7.5 million. Funded projects included the following and others:

- Connected private septic systems to a public sewer system;
- Converted agricultural lands into forested lands;
- Implemented nitrogen-reduction practices at diary farms (e.g., changes to feed management, manure handling, and fertilizer application).

We suggest a similar program could be developed to include any waters within Virginia where there is a nutrient issue. Such a program could be utilized to reduce nutrients to SML to help prevent cyanobacterial blooms. Funding from the General Assembly may help make such a program a reality.

Riparian/Shoreline Buffers

The James River Riparian Buffer Program helps landowners in the James River watershed install vegetative buffers along streams and rivers on their properties. Riparian buffers include trees, shrubs, and other vegetation along waterways. Among the environmental services they provide, riparian buffers improve water quality by filtering runoff from adjacent land, which prevents pollutants from reaching the waterway. The program leaders, the James River Association and the Chesapeake Bay Foundation, work with landowners to select native trees and plants, and then volunteers with the organizations plant and maintain the buffer for the first three years. Stakeholders in the SML watershed could reach out to the program leaders to investigate if such a program could be similarly implemented along the Blackwater and Roanoke rivers. Funding that supports the program along the James River is unavailable for the Roanoke and Blackwater rivers because these rivers are outside the Chesapeake Bay watershed. However, if a pay-for-outcomes program (see above) is established across Virginia, such a buffer program could be submitted for funding as a cost-effective practice to reduce nutrient inputs in SML.

Soil Erosion

While working on this project, we heard stakeholder complaints regarding soil erosion during clearing and construction around SML. Such erosion negatively impacts SML by increasing the amount of sediment and nutrients into the water. Complaints of soil erosion should be communicated to the local erosion and sediment control authority. Complaints may also be made to DEQ's regional office (Blue Ridge Regional Office) or its online Pollution Reporting and Environmental Permitting (PREP) portal (https://portal.deq.virginia.gov/). The state and localities may consider additional measures, control practices, and requirements to reduce soil erosion in the area surrounding SML.

Wake Boats

Wake boats are designed to displace large quantities of water into tall wakes that are 2-3 times larger than wakes from non-wake boats. Wake boat characteristics that negatively impact lakes include the effects of waves on shorelines and far-reaching propeller turbulence. Wake boats can transfer up to 12 times more energy to shorelines than non-wake boats, and the formed wakes while wake-surfing can require up to 600 feet to dissipate (Ortiz, 2024). Thus, their wakes can lead to shoreline erosion, which can contribute nutrients to the lake. In shallow waters, wake boats may also cause sediment resuspension, which can release nutrients into the water.

Recommended wake boating area requirements as described by Ortiz (2024) include the following:

- Minimum depth of 20 feet throughout the entire wake boating area.
- Minimum distance from shore of 600 feet.
- Minimum lake area of at least 40 contiguous acres.
- Minimum area per boat of at least 10 acres.

The Tri-County Lakes Administrative Commission's Wake Education Task Force recommends that wake boats stay 200 feet from shore (TLAC, 2025). Currently, most of SML is recommended as a safe towing area (Figure 13). Wake boating guidelines and requirements may need to be updated to prevent resuspension of sediments and protect SML's shoreline from erosion, and thereby reduce potential nutrients available to cyanobacteria.

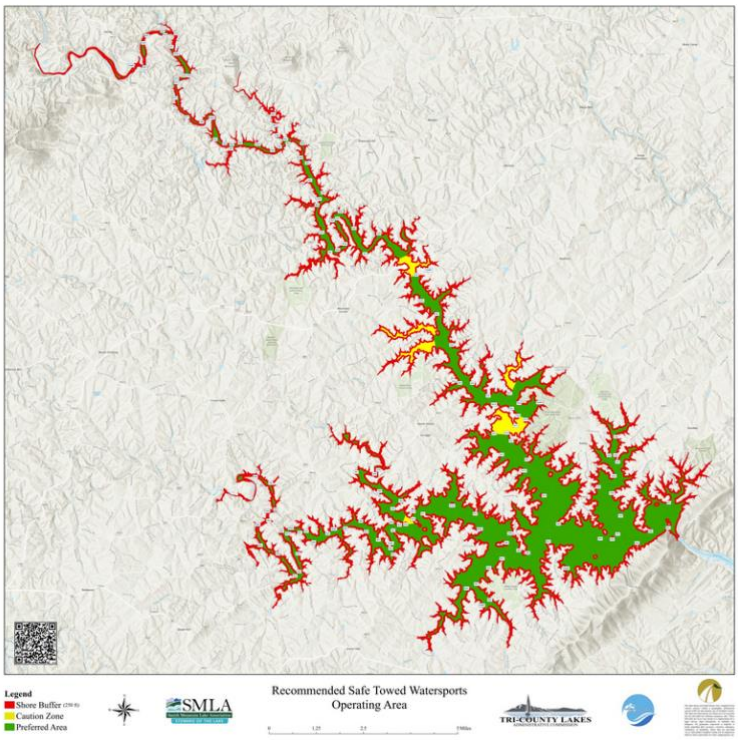

Figure 13. Map of recommended Safe Towed Watersports Operating Area for Smith Mountain Lake showing shore buffers (red), caution zones (yellow) and preferred areas (green). Source: Tri-County Lakes Administrative Commission.

Education Programs

Educational programs can help make residents and lake users aware that their actions can help improve lake water quality or make it worse. Yet, it can be difficult for people to understand: 1) what happens on land affects the lake, and 2) nutrients impact the lake and contribute to bloom events. Most lake users care about bloom events; they want to be able to use the lake (avoid no-swim advisories), but people typically have a harder time caring about nutrients entering the lake. It can be a difficult concept to understand that nutrients in runoff feed the cyanobacteria that lead to bloom events. It can be even harder for individuals living upstream of the lake to see how their actions impact SML; they need to know that changes that benefit the river, also benefit SML.

The SMLA has been working to educate the users of the lake by engaging volunteer water monitors, conducting education programs in the surrounding school systems, providing programs for local civic organizations and others, and providing information through local news programs. These efforts are commended and should be continued. With such continued efforts, short messages provided through public service announcements on local TV and radio stations could be utilized, such as what to do if you see a bloom and how to report illegal discharges of boat waste. Longer messages could be provided in targeted workshops and programs focused on management issues. Partnering with experts to lead the program, such as the Tri-County Lakes Administrative Commission (TLAC), Smith Mountain Lake Water Treatment Plant, Virginia Cooperative Extension (VCE), Soil and Water Conservation Districts (SWCDs), state agencies, etc., can broaden the information provided. Topic ideas may include the following and more:

- Cyanobacteria and recreational advisories,
- Installation of shoreline/riparian buffers,
- Proper fertilization and maintenance of a lawn (including information about Virginia Tech's Soil Testing Lab),
- Homeowner information on septic systems (including how to obtain financial assistance for septic system repairs or replacements: VDH's Septic and Well Assistance Program [SWAP], Southeast Rural Community Assistance Project [SERCAP]),
- Virginia Conservation Assistance Program (VCAP),
- Virginia Trees for Clean Water Grant Program.

Volunteer Activities

The SMLA has recently established the Dock Watch program, where volunteers help to report water quality and bloom assessments. Examples of additional volunteer outreach may include:

- Celebrate the reasons people value SML: organize a photo contest, slogan contest (e.g., "Feed your lawn, not the lake"), and/or art exhibit (children and adult levels) focused on SML. When people care about the lake, they are more likely to work to protect it.
- Establish a "Lake Smart Home Program" where homeowners who establish a shoreline buffer, implement stormwater BMPs (or whatever criteria are established) receive a "Lake Smart Home" garden flag to install by their driveway. Groups in other areas of Virginia have reported success with similar programs.
- Help establish shoreline/riparian buffers on properties willing to have them and blog about the experience, such as observed benefits to lake and wildlife along with less lawn maintenance. Once there are enough homes that have shoreline buffers, organize a "Lakeshore Buffer Tour" (like a home/garden tour) to showcase the buffers.

Cyanobacterial Bloom Management Options

There are numerous within-lake management practices, often incorporated by drinking water treatment facilities, that could be considered to help prevent the recurrence of HABs in SML. Also, if a bloom occurs, these measures could be used to reduce the magnitude and extent of the bloom; however, nutrient reductions are needed for long-term success. Several documents that summarize numerous in-lake control strategies are provided below and in the tables that follow:

- *Strategies for Preventing and Managing Harmful Cyanobacterial Blooms (HCB-1)* (ITRC, 2020) by the Interstate Technology and Regulatory Council includes a section on management controls (Section 6). A table of in-lake strategies designed to prevent or intervene in cyanobacterial blooms is provided. The table provides a brief description of each strategy and summarizes each strategy's history of use, relative costs, and application. The *HCB-2* (ITRC, 2022) offers an interactive tool (https://hcb-2.itrcweb.org/management-criteria-tool/) to help stakeholders determine in-lake management strategies. Each listed strategy is linked to a fact sheet with more information.

- Kibuye et al. (2021a; 2021b) reviewed and compared numerous cyanobacterial controls based on chemical, mechanical, and biological methods. Their findings, summarized in Tables 26 and 27, may be of interest to the SML stakeholders.

Table 26. Summary of reviewed chemical control strategies for cyanobacterial control.*

Strategy	Strengths	Limitations	Considerations	Environmental Impacts
H_2O_2-based algaecides	-Rapid water quality improvements -Cheap management option -Selectivity to cyanobacteria -Can contribute to the degradation of toxins -Degrades into H_20 and 0_2 -No accumulation in the environment	-Short-term bloom control -Cell lysis/toxin release -Rapid H_20_2 decay results in short residence time -No internal nutrient control -Application challenges in large sources -Optimized treatment designs may be needed for benthic blooms -May increase nutrients in the water column	-Federal or state government regulatory permits and monitoring requirements may apply -Timing treatment with respect to growth stage to minimize metabolite generation and rapid H_20_2 decay -Accurate dosing to reduce chances of metabolite release and ecological impacts -Timing treatment during sunny periods to enhance the treatment effect -Phytoplankton composition can influence treatment performance due to their rapid breakdown of H_20_2 -Granular H_20_2 can help target benthic blooms -Rebound influenced by external and internal nutrient loading	-Can impact non-target species -Promotes dominance of green algae
Cu-based algaecides	-Rapid water quality improvements -Cheap management option -Long residence time in water	-Short-term bloom control -Cell lysis/toxin release -Cyanobacteria can develop tolerance to Cu -Optimized treatment designs may be needed for benthic blooms -No internal nutrient control -Application challenges in large sources -Cu accumulation in sediments	-Federal or state government regulatory permits and monitoring requirements may apply -Accurate dosing to reduce chances of metabolite release, accumulation in water, sediments, and ecological impacts -Granule size can be optimized to help target both pelagic or benthic blooms. -Rebound influenced by external and internal nutrient loading	-Can impact non-target species and result in fish kills -Cu accumulation in water column and sediments
Lanthanum Bentonite	-Internal P binding -Offers Long term benefits (2-9 yrs.)	-Performance impacted by organic matter content -Can be ineffective if external loading is not controlled	-Ineffective when external nutrients are not controlled	-La Ions accumulation in water and sediments -Potential bioaccumulation in aquatic organisms
Alum/calcium/ ferric	-Nutrient (P) and some direct algal control -Long-term benefits (1-15 yrs.)	-Water quality dependence e.g., pH, redox state, alkalinity -Influence of source water morphology -Influenced by application methods	-Can be ineffective if external loading is not controlled -Dose optimized treatment based on available P -Al treatments may not offer effective control for polymictic lakes with frequent sediment resuspension -Fe treatments can be augmented with oxygenation of the water column to improve P binding -Ca treatments can influence bulk pH in the water column	-Metal ions accumulation in water and sediments

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Table 27. Summary and comparisons of mechanical and biological methods for cyanobacterial control.*

Strategy	Strengths	Limitations	Considerations	Environmental Impacts
Artificial mixing	-Increases water column DO -Suppress release of reduced species (P, Fe, Mn, NH_3) -Cyanobacterial control via sedimentation losses and light limiting conditions -Destratifies water column -Can offer proactive and reactive control -Offers long term benefits (up to 7 yrs.) with continuous operation	-Resuspension of sediment layer nutrients/ions in the water column -Sedimentation of organic matter -Installation and operational cost	-Ineffective in shallow lakes/ reservoirs with a large surface area -May require continuous operation -Can be ineffective when external nutrients are not controlled	-Beneficial ecological impacts -Warming of the water column may impact cold-water habitats
Hypolimnetic oxygenation & aeration	-Raise DO in bottom layers -Suppress release of reduced species (P, Fe, Mn, NH_3) -Avoids mixing of nutrients in the water column -Can offer proactive and reactive control -Long term benefits (10-23 yrs.)	-Resuspension of nutrients in the water column -Sedimentation of organic matter -Installation and operational cost	-Success impacted by system optimization based on source geometry and depth -May require a continuous operation or precise timing for effective performance -Can be ineffective when external nutrients are not controlled -Can be influenced by sediment composition of Fe, Mn, and Al	-Beneficial ecological impacts -Warming of the water column may impact cold-water habitats
Sediment dredging	-Removal of nutrient-rich sediments -Increase in DO levels	-Operational cost -Sediment disposal challenges -Suspension of sediment-bound nutrients and metal ions	-Ineffective when external nutrients are not controlled -Not ideal for large lakes/reservoirs	-Disturbance of microbial communities -Suspended sediment-bound materials may be toxic to aquatic life -Disposed of sediments may cause further ecological impacts
Sonication	-No treatment residuals -Potential selectivity to cyanobacteria	-Limited field-scale trials and treatment longevity evaluation -Potential toxin release -Limited process control in the field	-Treatment efficiency can be impacted by source water size /geometry -Field-scale success may require operation at high frequencies and power -Limited field-scale application history and success	-May impact aquatic organisms
Biological control	-Pelagic & benthic bloom control -Proactive & reactive strategy -No metabolite release -No treatment residuals in the water column -Planting of macrophytes can also control internal nutrients -Long term benefits (4-10 yrs.) with biomanipulation -Minimal environmental impacts	-Biomanipulation and straws not suitable for nutrient control -Straws are not effective in sources with low DO -Treatment effect is localized in areas of straw application -Performance of straws is delayed until the onset of decomposition -Limited directives on ideal macrophyte cover and fish removal/ addition rates	-Higher biomanipulation success in shallow than stratified lakes -Macrophytes may be limited in eutrophic sources -Influenced by continued external nutrient inputs	-Long term shift of aquatic ecosystem composition

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Future Monitoring

The water quality and bloom-related data presented and analyzed in this report were provided by ongoing monitoring programs by DEQ and Ferrum College/SMLA. These programs are well established and extensive. We recommend the continued commitment to these efforts and the useful data they provide. Further, the SMLA established a Dock Watch Program in 2024 to monitor potential HAB activity from docks around SML. Through this new program, volunteers are trained by scientists with the National Oceanic and Atmospheric Administration (NOAA) to identify common cyanobacteria in SML. Some volunteers collect near-surface water samples from their assigned dock every other week from April to October, and others collect samples every other week throughout the year. The data are uploaded to NOAA's Phytoplankton Monitoring Network (PMN) database and recorded in a SMLA Dock Watch spreadsheet. Further, DEQ has added cyanotoxin monitoring at approximately 15 stations in SML during routine lake monitoring runs annually from April to October. As these programs develop, we provide suggestions for cyanobacteria and water quality monitoring to consider.

Cyanobacteria Monitoring

Below is some literature regarding cyanobacteria monitoring to consider when updating monitoring programs or for future expansions of programs in SML.

- *Strategies for Preventing and Managing Harmful Cyanobacterial Blooms (HCB-1)* (ITRC 2020) provides information on sampling planktonic, benthic, and attached cyanobacteria. The document also covers ways to evaluate cyanobacteria abundance and emerging monitoring techniques (Section 4). The *HCB-2* (ITRC, 2022) includes more information about cyanotoxins (Section 2) and monitoring benthic cyanobacteria (Section 3). The *HCB-2* also offers an interactive tool (https://hcb-2.itrcweb.org/monitoring-tool/) for determining methods of monitoring cyanobacteria and cyanotoxins and includes direct links to information found within the *HCB-1* and *HCB-2* documents.

- Almuhtaram et al. (2021) reviewed numerous monitoring tools used in identifying cyanobacterial blooms (Table 28). The tools are organized into three different tiers: 1) simple and inexpensive tools to monitor biological activity within a lake (e.g., Secchi disk depths, chlorophyll-*a* concentrations, drone flights, adenosine triphosphate [ATP] concentrations); 2) tools used to identify the presence and quantity of cyanobacteria (e.g., microscopic enumeration, phycocyanin extraction, next-generation sequencing [NGS]); and 3) tools for the detection of toxins or genetic markers for cyanobacteria able to produce toxins (e.g., ELISA [enzyme-linked immunosorbent assay] test kits, qPCR [quantitative polymerase chain reaction] analysis). Their proposed monitoring framework is designed to accommodate various skill-level requirements and financial resources.

Table 28. Summary of cyanobacteria monitoring tool capabilities.*

Technology		Cost per sample	Turnaround time	Pelagic or Benthic	Accuracy	Interferences
Tier 1	Visual inspection	No cost	Immediate	Pelagic	Cannot estimate cell concentrations	Cannot distinguish species
	chlorophyll a extraction	Moderate	<1 day	Both	Moderately correlates to cyanobacteria	Low
	chlorophyll a fluorescence	Moderate	Real-time	Pelagic	Moderately correlates to cyanobacteria	Turbidity and other fluorescent compounds
	ATP	Low	<10 min or real-time	Pelagic	Measure of biological activity	Presence of bacteria
	Drones	Low	<1 day	Pelagic	Captures surface conditions only	Poor weather, flight restrictions
Tier 2	Microscopy	Low	<1 day	Both	High	Low
	Phycocyanin extraction	Moderate	<1 day	Both	Strong correlation to cyanobacteria	Cell quota varies among species; turbidity and other fluorescent compounds
	Phycocyanin fluorescence	Moderate	Real-time	Pelagic	Strong correlation to cyanobacteria	Cell quota varies among species; turbidity and other fluorescent compounds
	Satellite remote sensing	Low	>1 day	Pelagic	Captures surface conditions only	Cloud cover, orbital period
	Photonic systems	Low	<1 day	Pelagic	Measure of phycocyanin	Turbidity and other fluorescent compounds
	Automated cell imaging	High	<10 min	Pelagic	High	Low
	Biosensors	Moderate	<1 day	Pelagic	Measures specific cyanobacteria strains or species	Low
	NGS	High	<1 day	Both	High	Low
Tier 3	qPCR	Moderate	<1 day	Both	Presence of genes does not indicate metabolite production	Low
	ELISA	Low	<1 day	Both	Variable cross-reactivity among cyanotoxin variants	Presence of partially degraded cyanotoxins; false positives may occur
	Gas/liquid chromatography-mass spectrometry	High	<1 day	Both	High	Low

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Water Quality Monitoring

Smith Mountain Lake has extensive water quality data that span decades. Collected data at monitoring stations over this time period generally indicates that nutrient concentrations are declining while bloom occurrences and bloom indicator variables (i.e., Chl-*a*) have increased. Thus, more monitoring of stream inputs, weather variables, and within-lake drivers may be useful in identifying locations and conditions resulting in blooms. Below, we offer suggestions for data collection programs to consider regarding such drivers.

- Monitoring could include visual stream assessments in the tributaries to SML to gain a better understanding of the conditions in and surrounding streams and rivers upstream of the lake. During such assessments, individuals could walk/paddle the stream/river and assess its overall condition and document issues that could impact the water quality, e.g., the presence of pipes entering the stream, bank erosion, livestock with access to the stream, etc. The California Association of Resource Conservation Districts (2001) has developed a visual assessment protocol and data sheets intended for use by volunteers with limited equipment and training that could be useful for conducting similar assessments in the SML watershed. Having a better understanding of the current conditions within tributaries could help identify new areas to target monitoring efforts and implement BMPs.

- We recognize the logistical challenges in quickly responding to bloom reports for cell count and toxin monitoring. However, it would be useful to have teams prepared to also sample other water quality variables during bloom responses. Co-located measures of temperature, nutrient availability and water clarity may help to better assess the role of such drivers at the specific location and timing of bloom occurrence.

- Blooms at SML tend to be localized and short term, suggesting that weather and within-lake conditions are potential drivers, particularly low wind and high temperatures that increase lake stratification. This stratification supports upper, high-light layers conducive to bloom formation. Growing season monitoring of light profiles, photic depths, and mixing depths may indicate locations and conditions most vulnerable to bloom occurrences. Coincident monitoring of other water quality variables related to light attenuation (Chl-*a*, total suspended solids, and dissolved organic matter) would complement these efforts.

- Improved monitoring of meteorological variables will assist in HAB forecasting and assessments. Wind direction and speed influence lake mixing, where low wind can lead to stratification and thus higher light availability for cyanobacterial growth. However, high wind and lake mixing may result in redistribution of nutrients (particularly phosphorus) associated with sediment-water interfaces. As such, a spatially distributed, wind-monitoring network could provide additional information to assess bloom drivers. Likewise, precipitation is poorly measured across SML. Rain gauges would assist in understanding inputs for models, but also for understanding loading and storm impacts on nutrients in the lake. The recently initiated SML Dock Watch program and the buoy monitoring efforts suggested below could help support such measurements.

- Buoys can be equipped with real-time, high-frequency sensors for potential HAB forecasting and management in lake systems. They can be used to continuously monitor key ancillary parameters that have been mentioned above such as chlorophyll-*a*, temperature, and photosynthetically available radiation to monitor conditions conducive to HABs (e.g., stratification and light availability) or to constrain models providing HAB forecasts (see research section below). Buoy monitoring systems can also include sensors that measure phycocyanin concentrations directly, use custom open-source data acquisition and processing, and off-the-shelf sensors for a fraction of the cost of commercial systems (Miller et al., 2022).

Future Research Directions

Below, we provide some recommendations to consider when exploring new research directions regarding within-lake management strategies, remotely sensed assessments, identification of nutrient sources, and modeling approaches.

Within-lake Management Strategies

- As discussed above, within-lake management options include adding phosphorus binding agents to reduce dissolved phosphorus concentrations. Prior to a large-scale field-scale trial, it would be useful to conduct a laboratory analysis of the phosphorus content of lake sediments and the efficacy of phosphorus-binding agents to mitigate phosphorus release from lake sediments. This analysis would use water-sediment cultures collected from different areas of the lake to test different-binding agents and dosing rates. These experimental trials would also allow assessments of the effects of P-binding agents on cyanobacterial community composition and toxin production.

- The potential use of chemical algicides (see Table 26) could be explored for localized reduction of potential HABs and application within SML[3]. This effort could take the form of benchtop studies or trial application in coves within SML. While algicidal bacteria show significant potential for cyanobacterial bloom control (Coyne et al., 2022; Gallardo-Rodrıguez et al., 2019), current effectiveness in real-world recreational settings remains limited.

Remote-sensing Technologies

- In this report, we presented a first assessment of the ability of satellite imagery to identify timing and discrete locations of potential blooms in SML. Further analysis of these high spatial resolution time series data along with water quality, weather, and lake profile data (i.e., stratification and light availability) may offer more insight into conditions supporting bloom development. Further, these data, while not predictive in time, may

[3] Note: Algicide applications in lakes in Virginia require a General Permit for Discharges Resulting from the Application of Pesticides to Surface Waters of Virginia (VAG87; 9VAC25-800-60).

also help indicate other lake locations to track potential bloom development following bloom reports in specific locations.

- Recent work has used unmanned aerial vehicles (i.e., drones) to assess lake Chl-*a* and phycocyanin, which is related to microcystin concentrations, as well as aerosolization of cyanobacterial cells (Hanlon et al., 2022). Stakeholders of SML could consider conducting such work along with spatially extensive synoptic water quality sampling to explore interactions between drivers and potential blooms at a high spatial resolution.

Identification of Nutrient Sources

- If there are known potential sources of *E. coli* and thus associated nutrients, either upstream or in the vicinity of monitoring stations (particularly for stations 14, 1, 5, and 11 in the SML Water Quality Monitoring Program), it would be beneficial to establish monitoring stations upstream and downstream of the potential source. Further testing with microbial source tracking, species-specific DNA markers or environmental DNA (eDNA) could help to identify sources of fecal contamination at these sites. Such analyses could determine whether fecal contamination is coming from humans, livestock, pets, wildlife or a combination of sources. Monitoring for optical brighteners, which are commonly found in laundry detergents, could also be used to detect illicit discharges, sewer leaks, and failing septic systems.

- Different sources of nutrients (e.g., fertilizer, sewage, livestock manure) have distinct isotopic ratios[4] for various elements (e.g., nitrogen, oxygen). Isotopes can be used as a tracer of sources when the different sources have significantly different ratios. For example, by analyzing the isotopic composition of nitrate (NO_3^-) in water, researchers have been able to determine the relative contributions of various nitrogen sources in groundwater and streams (e.g., Gautam and Iqbal, 2010; Showers et al., 2008; Tihansky and Sacks, 1997; Xia et al., 2017). The use of stable isotopes may be a viable way to identify the relative inputs of fertilizer and animal waste as sources of pollution in SML. However, the application of this method has limitations, e.g., may be unable to differentiate between septic effluent and livestock waste contamination (Zhang et al., 2019).

- Smith Mountain Dam has a pumped-storage system where water from below it is pumped back into SML when electricity demands are low, and water flows downstream again, generating electricity, when electricity demand is high. This process involves the movement of large amounts of water on a frequent basis. Stakeholders have noted that when water is pumped back into SML from downstream, it makes a big difference near the dam in turbidity. Thus, operation of Smith Mountain Dam has the potential to impact the water quality of SML by injecting downstream water (and potentially nutrients and cyanobacteria) from Leesville Lake, which has different physical, chemical, and

[4] Isotopes of an element (e.g., N^{14}, N^{15}) have the same number of protons and electrons but differ in the numbers of neutrons so have different atomic masses, making it slightly harder to make and break bonds with the heavier element. Scientists can measure the ratio of the heavier element to the lighter one to study environmental processes.

biological properties, into SML. Gaining a better understanding of the impacts on water quality from the operation of the pumped-storage system could provide insights on how to help reduce and prevent future cyanobacterial blooms.

Modeling Approaches

- We conducted watershed modeling (via SWAT) to estimate streamflow rates and associated non-point source nutrient and sediment loading to SML, along with scenario modeling to estimate the potential for buffers to reduce loads. However, our modeling was constrained by only having streamflow data to calibrate. Future efforts could focus on data collection needs to calibrate models using both streamflow and nutrient concentration data and to incorporate point sources and current management practices into a revised model. Further, the SWAT model has a reservoir function that could help to estimate residence times within the lake, where longer residence times may lead to more favorable conditions for bloom development. Last, within-lake process-based models (as opposed to SWAT) may offer a better representation of drivers of bloom development, such as stratification and mixing, light availability, and temperature.

- New research efforts are focused on using high frequency monitoring to inform forecasting of impending ecological events, known as ecological forecasting. Particular focus has been on lake systems and reservoirs, including prediction of low-oxygen conditions, stratification, and harmful algal blooms. The real-time data from buoys mentioned above can be coupled with predictive models using artificial intelligence (AI) or process models to forecast bloom conditions several days in advance (Rousso et al., 2020). Additionally, real-time data from buoys can be integrated with satellite imagery and coupled with uncertainty quantification methods to create more robust forecasting systems that provide managers with probabilistic predictions of bloom risk rather than simple point estimates (Carey et al., 2025; Morón-López et al., 2021). Given the existing and new monitoring efforts at SML discussed in this report, this predictive modeling is a new direction to consider that could leverage such data collection programs.

Conclusions

With support from the Governor and General Assembly, funding for the first year of this effort came from the general fund to conduct a study of harmful algal blooms occurring at Smith Mountain Lake (SML). This effort involved the successful formation of a partnership with the Virginia Department of Environmental Quality (DEQ), Smith Mountain Lake Association (SMLA), Virginia Department of Health (VDH), and the Virginia Water Resources Research Center (VWRRC) at Virginia Tech. We worked together to evaluate the conditions that have led to the appearance of HABs in SML. Additionally, we sought input and suggestions from an advisory committee comprised of researchers from Ferrum College, Virginia Commonwealth University, and Virginia Tech to provide guidance on the study and recommendations on ways to prevent future HAB occurrences.

Accomplishments

This study had a one-year timeframe, and we accomplished our study objectives during this time. The following list of accomplishments signifies the efforts made to meet the established goals.

Webtool

- Developed the SML Webtool (http://52.5.129.122/react/) to store and share data and analyses among stakeholders.
- Developed a User Guide for the Webtool.
- Populated the Webtool with the following data:
    - Water-quality data from DEQ monitoring sites immediately upstream of and within SML.
    - Total phosphorus data from Ferrum College tributary monitoring sites for SML.
    - Remote sensing–derived chlorophyll index data for SML.
    - Delineation of the SML watershed.
    - Land cover change from 2001–2023 from the National Land Cover Database (NLCD) for the SML watershed.
    - Land cover data from the 2016 Virginia Geographic Information Network (VGIN) for the area.

HAB-related Data

- Reviewed and summarized historic potential HAB reports for SML as submitted by the public to VDH.
- Obtained and summarized VDH phytoplankton data collected in SML.
- Explored the utility of remote sensing for bloom identification in SML.
- Derived Normalized Difference Chlorophyll Index images for nine dates in 2023 to provide high-resolution (10-meter resolution) views of bloom dynamics.

DEQ Water-quality Data

- Obtained and analyzed DEQ water quality datasets that included 22 monitoring stations (with up to 17 parameters per site) that were monitored between 1994 to 2024.
- Imported 62,186 water quality records into the PostGIS database for statistical analysis and interactive visualization.
- Standardized each variable into a regular, calendar-month time series by calculating a monthly average for each variable to obtain one value per month per station.
- Quantified long-term changes with the Theil–Sen estimator to monthly time series data.
- Derived the median annual rate of change for each variable.
- Assessed the significance of each trend with the Mann–Kendall test ($\alpha = 0.05$).
- Assessed correlations among water quality variables.

SML Water Quality Monitoring Program Data

- Obtained and described various water-quality and phytoplankton datasets from the SML Water Quality Monitoring Program led by Ferrum College and the SMLA.
- Calculated descriptive statistics for the following long-term data obtained by the program:
    - Total phosphorus (TP) concentrations from 19 tributary stations (2002–2024).
    - Chlorophyll-*a* and TP concentrations along with Secchi disc depths used to estimate a trophic state index from 56 stations in the lake (2002–2024).
    - Phytoplankton abundance at 19 lake stations (14 from horizontal tows, and 5 from vertical tows; 2010–2023).
    - Temperature, dissolved oxygen, pH and conductivity from five depth-profile stations within the lake (2005–2024).
- Estimated annual loads of phosphorus into SML using tributary TP concentration data and estimated flows from the Soil and Water Assessment Tool (SWAT) model.

Land-use Analysis

- Assessed land cover change between 2001 and 2023 using the National Land Cover Database (30-meter resolution).
    - Examined and compared urban area changes within the two watersheds contributing to SML: Blackwater and Roanoke.
    - Examined and compared urban area changes within lake/stream buffers for SML, Blackwater River, and Roanoke River.
    - Examined and summarized land cover transitions within the SML watershed that involved shifts from forest and agricultural areas to urban land.
- Utilized 2016 Virginia Geographic Information Network (VGIN) data to provide more detailed land use descriptions for the SML watershed (1-meter resolution).
    - Described land cover for buffers set at 500 m and 1 km surrounding the entirety of SML and separately for the Blackwater and Roanoke arms.

Watershed Modeling

- Used SWAT to assess nutrient and sediment loads from non-point sources into SML.
    - Simulated hydrologic and water quality processes in the Blackwater River Basin and Roanoke River Basin.
    - Estimated sediment, total nitrogen, and total phosphorus loads from individual subbasins under current land-use and climatic conditions.
- Conducted a scenario simulation to assess potential changes in nutrient loading when 30-meter stream buffers are implemented in the Blackwater River Basin.

Recommendations

The Governor and General Assembly requested we provide recommendations for prevention of further HAB occurrences within SML. Within this report, we have presented various management options for nutrient and bloom reduction strategies, along with suggestions for future monitoring and research efforts. Our recommendations include the following:

- Make state funding available to the Roanoke Regional Water Pollution Control Plant to overhaul their treatment process to better control nutrient inputs into SML.
- Implement a Pay-for-Outcomes Nonpoint Source Pollution Reduction Grant Program open to all waters within Virginia where there is a nutrient issue.
- Consider additional measures, control practices, and requirements to reduce soil erosion in the area surrounding SML.
- Update wake boating area requirements (e.g., minimum depth of 20 feet).
- Provide educational programs to help residents and lake users be aware their actions can help improve lake water quality.
- Establish new volunteer outreach programs (e.g., photo contests, Lake Smart Home Program, Lakeshore Buffer Tour).
- Study and incorporate, as applicable, within-lake management practices utilized by drinking water treatment facilities to help prevent or manage cyanobacterial blooms.
- Encourage the continuation of DEQ and volunteer monitoring programs established within SML and expand or update water monitoring efforts in SML to target data needs (e.g., monitor for total hardness, sulfates, chlorides, and TSS; conduct visual stream assessments; utilize bloom report response kits; develop light profiles; establish weather stations; install buoys with real-time, high-frequency sensors; etc.).
- Conduct research to study within-lake management strategies, utilize remote-sensing technologies, identify nutrient sources, and employ various modeling approaches.

Continuation of Study

Although much was accomplished given the one-year timeframe, more work is needed to better understand the reasons for cyanobacterial blooms and how to prevent their occurrence within SML (as well as in other waters in Virginia). Additional funding provided from the state for the continuation of this work could address aspects of the study we were unable to complete within this past year and allow us to initiate new research efforts outlined in this report of most interest to the SML stakeholders. Depending on resources allotted and the timeframe provided, we can envision accomplishing the following:

- Add data from the SML Water Quality Monitoring Program (Ferrum/SMLA) to the SML Webtool.
- Analyze Ferrum/SMLA long-term data similarly as done for DEQ's long-term data (e.g., Theil–Sen estimator for trends, Mann–Kendall test for significance, correlations).
- Analyze remote sensing data in relation to bloom-related and water-quality data, to gain a better understanding of lake conditions during blooms.
- Improve SWAT model results by adding input data about point sources.

- Run more management options using the SWAT model (e.g., buffers in the Roanoke watershed and buffers around SML).
- Provide training and/or advice on conducting new monitoring efforts to meet specified goals within the SML watershed.
- Facilitate collaborations between researchers and SML stakeholders to initiate new research areas of most interest to stakeholders.
- Perform other tasks desired by the funder and SML stakeholders.

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Appendix A: Potentially Toxigenic (PTOX) Cyanobacteria Taxa

List of regional potentially toxigenic (PTOX) cyanobacteria taxa as listed in VDH's 2024 Cyanobacteria Bloom Response Job Aid. The listed taxa are based on literature reviews, other state plans, and discussions with VDH's regional partners.

- Anabaena
- Anabaenopsis
- Anagnostidinema
- Aphanizomenon
- Chrysosporum
- Cuspidothrix
- Dolichospermum
- Lyngbya
- Geitlerinema
- Microcoleus
- Microcystis
- Microseira
- Nodularia
- Nostoc
- Oscillatoria
- Phormidium
- Planktothrix
- Raphidiopsis
- Sphaerospermopsis
- Woronichinia

The PTOX taxa list will be reviewed at least annually or more frequently as needed by HAB Task Force staff. Updated March 2024.

Appendix A References

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Appendix B: Smith Mountain Lake Webtool

The development of the Smith Mountain Lake water quality visualization tool required a robust approach that could efficiently handle spatial data, provide interactive visualizations, and support scalable backend operations. GeoServer, Django, PostGIS, and React were chosen for their respective strengths in geospatial data management, web development, and interactive user interfaces. The figure below shows the key development technologies used in its implementation.

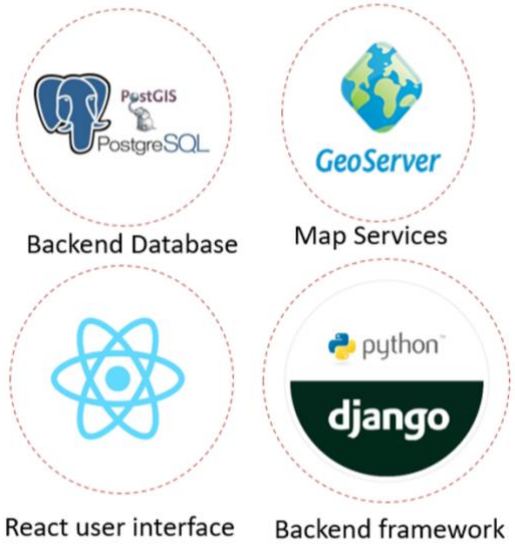

Figure B-1. Technology architecture of the SML Webtool, showing the integration of PostGIS for geospatial data storage, GeoServer for serving spatial data via web services (WMS/WFS), Django for backend processing and application programming interface (API) development, and React for frontend user interaction and visualization. The system is deployed with Amazon Web Services, Inc. to ensure scalability and secure cloud-based data access.

PostGIS, an extension of PostgreSQL, was used to manage geospatial data, providing advanced spatial querying capabilities for handling large volumes of water quality measurements and geospatial operations. It enables efficient storage and retrieval of georeferenced data and is well-suited for managing large datasets. Its scalability makes it an ideal choice for expanding the webtool to additional lakes or monitoring sites in the future

GeoServer was selected as the geospatial server because of its ability to efficiently serve spatial data using Web Map Services (WMS) and Web Feature Services (WFS). It allows seamless integration of spatial datasets into web applications, providing optimized map rendering and geospatial querying. Its support for open standards ensures interoperability with various GIS platforms, making it a good choice for visualizing water quality data across multiple monitoring stations, and in the future for satellite imagery and land use/cover visualization.

Django was chosen as the backend framework due to its reliability, scalability, and ability to handle complex data operations efficiently. Its built-in object–relational mapping (ORM) simplifies database interactions, while its representational state transfer (REST) framework

enables structured API development. Django's security features and robust architecture also make it an ideal choice for managing user requests and processing large datasets while ensuring seamless communication between the frontend and the database.

React was selected for the frontend to create a dynamic user interface. With its component-based architecture, React ensures smooth rendering of interactive graphs, maps, and filtering options, providing users with a seamless experience when exploring water quality data. It is well-suited for real-time data interaction.

By combining these technologies, the webtool achieves a balance between performance, scalability, and user experience. The integration of GeoServer, Django, PostGIS, and React ensures that users can effectively explore water quality trends and potential correlations among selected variables. Future enhancements will continue leveraging this technology stack to introduce additional analytical tools for land change analysis and satellite image visualization, further strengthening the tool's impact.

The webtool was deployed using Amazon Web Services (AWS), ensuring high scalability, and secure cloud-based data management. Future enhancements will introduce additional analytical tools for land change analysis and satellite imagery visualization, further strengthening its impact.

Appendix C: Smith Mountain Lake Webtool – User Guide

Access the tool: http://52.5.129.122/react/
The Smith Mountain Lake Webtool is an interactive platform for exploring long-term water quality, land cover, and other data for the Smith Mountain Lake watershed. It integrates data from the Virginia Department of Environmental Quality (DEQ), Virginia Geographic Information Network (VGIN), National Land Cover Database (NLCD), Normalized Difference Chlorophyll Index (NDCI), and tributary monitoring data from Ferrum College.

Main Interface Layout

- **Left Panel – Interactive Map:**
  Use the map to explore:
  - DEQ water quality monitoring sites (clickable)
  - Ferrum sites (clickable)
  - 2016 VGIN high-resolution land cover
  - NLCD land cover change (2001–2023)
  - NDCI index (2023-06-02)
  - Smith Mountain Lake boundary and
  - Roanoke and Blackwater rivers

  Zoom in/out (click on the "+" or "-" boxes in the upper left corner)
- **Right Panel – Graph and Controls:**
  After selecting a map feature (site or subbasin), the right panel displays:
  - **Time-series plots** for water quality variables (e.g., pH, nitrogen, temperature)
  - **Scatter plots** for variable comparison (e.g., DO vs. temp)

How to Use the Tool

1. **View DEQ Water Quality Data** (select "Sites" on the map layer toggle)**:**
   a. Click on any DEQ monitoring site.
   b. Use the dropdown by "Select Variable" and select a variable (e.g., pH, DO).
   c. View the time-series plot (blue: raw data, red: LOESS smoothed trend). Sen's slope is reported above the graph. A positive Sen's slope indicates an increasing trend, and a negative slope suggests a decreasing trend. The magnitude of the slope quantifies the average rate of change over time, with larger values indicating faster change.
   d. Enable "Compare" (slide button to the right) to create a scatter plot for two selected variables. The first variable will be on the x-axis, and the second variable will be on the y-axis. A Spearman's correlation value is provided above the graph. Spearman's correlation measures the strength and direction of association between the two variables. Positive correlations indicate that as one variable increases, the other also increases. In contrast, a negative correlation means that as one variable increases, the other tends to decrease. The strength of the relationship is indicated by how close the coefficient is to 1 for positive correlations and -1 for negative correlations. A Spearman's coefficient between 0.1 to 0.3 (or -0.1 to -0.3 for a negative relationship) would be weak. A coefficient between 0.7 to 1.0 (or -0.7 to -1.0) would be strong, indicating a clear tendency for one variable to change in a consistent way with the other.

2. **View Ferrum Sites Water Quality Data** (select "Ferrum Sites" on the map layer toggle)**:**
    a. Click on any Ferrum monitoring site.
    b. Use the dropdown by "Select Variable" and select Total Phosphorus (TP). Note only TP is available for Ferrum sites.
    c. View the time-series plot

3. **Explore Land Cover and Change:**
    a. Use the layer toggle in the map:
        i. Select "VGIN1m Land Cover (2016)" in the map legend to see land cover as determined in 2016. A legend explains what the different colors indicate (e.g., water, impervious, forest). Each pixel represents 1 square meter.
        ii. Select "Land Cover Change (2001–2023)" in the map layer toggle to see changes in land cover from 2001 to 2023. A legend shows if the land cover change goes from agricultural land to urban, from forest land to urban, or from forest to agricultural land. Data were obtained from the NLCD at a 30-m resolution, meaning each pixel represents 30 square meters.
    b. Zoom in/out (click on the "+" or "-" boxes in the upper left corner) to explore land use patterns or urban expansion.

4. **View Normalized Difference Chlorophyll Index (NDCI)**
    a. Use the layer toggle in the map
    b. Zoom in/out (click on the "+" or "-" boxes in the upper left corner) to explore NDCI patterns.

5. **Other Features:**
    a. Select "Smith Mountain Lake" to outline the lake.
    b. Select "Rivers" to show the Roanoke River and the Blackwater River.

Appendix D: DEQ Data Trend Analysis Methods and Results

To quantify long-term change, we applied the non-parametric Theil–Sen estimator to the monthly time series (i.e., Sen's slope estimate of the linear trend). By taking the median (the middle value in a dataset that has been ordered from smallest to largest) of all slopes and converting from days to years, we derived the median annual rate of change for each variable. We complemented this analysis with the Mann–Kendall test to assess the significance of each trend ($\alpha = 0.05$), without assuming normality or linear residuals (Helsel et al., 2020).

Results are provided for stations with more than 5 years of data in the following tables (listed in alphabetical order by DEQ station code). For each station, we report the first and last years of data used in the trend analysis, the total number of months analyzed, the Theil–Sen slope estimate (units per decade), and a simple "sig" (significant) or "ns" (not significant) flag based on Mann–Kendall significance (p-values < 0.05 are significant and p-values ≥ 0.05 are not significant).

As a sensitivity check, we also applied the Theil–Sen slope and Mann–Kendall tests to the raw, unaggregated observations and found similar slopes and probability values, confirming that the monthly-mean (monthly-average) approach adequately captures long-term trends.

Appendix D Reference

Helsel, D. R., Hirsch, R. M., Ryberg, K. R., Archfield, S. A., & Gilroy, E. J. (2020). *Statistical methods in water resources: Techniques and methods 4-A3*. U.S. Geological Survey. https://doi.org/10.3133/tm4a3 [Supersedes USGS Techniques of Water-Resources Investigations, book 4, chap. A3, version 1.1.]

4ABDA004.14 (Rt. 757 Bridge)

Station	Variable	Months	First Year	Last Year	Sen's Slope (/decade)	p-value	Sign.
4ABDA004.14	pH (standard units)	27	2017	2024	-0.80	<0.001	sig
4ABDA004.14	Dissolved Oxygen (mg/L)	27	2017	2024	-1.14	0.466	ns
4ABDA004.14	*E. coli* (CFU/100 mL)	23	2017	2024	-69.85	0.812	ns
4ABDA004.14	Temperature (Celsius)	27	2017	2024	3.72	0.381	ns
4ABDA004.14	Nitrogen (mg/L)	27	2017	2024	0.05	0.723	ns
4ABDA004.14	Total Phosphorus (mg/L)	27	2017	2024	0.00	0.617	ns

4ABSA000.62 (Mouth of Bull Run - SML)

Station	Variable	Months	First Year	Last Year	Sen's Slope (/decade)	p-value	Sign.
4ABSA000.62	Ammonia (mg/L)	177	1994	2024	-0.01	<0.001	sig
4ABSA000.62	Chloride (mg/L)	26	1994	2001	3.52	0.012	sig
4ABSA000.62	*E. coli* (CFU/100 mL)	143	2002	2024	0.00	<0.001	sig
4ABSA000.62	pH (standard units)	177	1994	2024	-0.13	<0.001	sig
4ABSA000.62	Temperature (Celsius)	178	1994	2024	1.09	<0.001	sig
4ABSA000.62	Fecal Coliform (CFU/100 mL)	41	1994	2012	0.00	0.003	sig
4ABSA000.62	Nitrogen (mg/L)	176	1994	2024	-0.09	<0.001	sig
4ABSA000.62	NO_x (mg/L)	177	1994	2024	-0.06	<0.001	sig
4ABSA000.62	NO_x + TKN (mg/L)	40	1994	2003	-0.17	0.002	sig
4ABSA000.62	Total Phosphorus (mg/L)	176	1994	2024	0.00	<0.001	sig
4ABSA000.62	Total Orthophosphate (mg/L)	177	1994	2024	0.00	<0.001	sig
4ABSA000.62	Sulfate (mg/L)	26	1994	2001	2.66	0.031	sig
4ABSA000.62	Total Suspended Solids (mg/L)	39	1994	2003	-0.81	0.012	sig
4ABSA000.62	Chlorophyll-*a* (µg/L)	161	1998	2024	0.09	0.514	ns
4ABSA000.62	Dissolved Oxygen (mg/L)	178	1994	2024	-0.06	0.809	ns
4ABSA000.62	Total Hardness (mg/L)	31	1997	2003	-2.33	0.799	ns
4ABSA000.62	Total Kjeldahl Nitrogen (mg/L)	39	1994	2003	-0.03	0.172	ns
4ABSA000.62	Secchi Depth (m)	163	1994	2024	0.00	0.426	ns

4ABWR002.50 (Lower Blackwater River - SML)

Station	Variable	Months	First Year	Last Year	Sen's Slope (/decade)	p-value	Sign.
4ABWR002.50	Ammonia (mg/L)	179	1994	2024	-0.01	<0.001	sig
4ABWR002.50	Chloride (mg/L)	26	1994	2001	3.28	0.040	sig
4ABWR002.50	Chlorophyll-*a* (µg/L)	162	1998	2024	0.29	0.012	sig
4ABWR002.50	*E. coli* (CFU/100 mL)	142	2002	2024	0.00	<0.001	sig
4ABWR002.50	pH (standard units)	178	1994	2024	-0.09	0.008	sig
4ABWR002.50	Temperature (Celsius)	179	1994	2024	1.51	<0.001	sig
4ABWR002.50	Fecal Coliform (CFU/100 mL)	43	1994	2012	0.00	0.004	sig
4ABWR002.50	Total Kjeldahl Nitrogen (mg/L)	53	1994	2022	-0.04	<0.001	sig
4ABWR002.50	Nitrogen (mg/L)	178	1994	2024	-0.09	<0.001	sig
4ABWR002.50	NO_x (mg/L)	171	1994	2024	-0.06	<0.001	sig
4ABWR002.50	NO_x + TKN (mg/L)	41	1994	2003	-0.18	0.007	sig
4ABWR002.50	Total Phosphorus (mg/L)	178	1994	2024	0.00	<0.001	sig
4ABWR002.50	Total Orthophosphate (mg/L)	170	1994	2024	0.00	<0.001	sig
4ABWR002.50	Total Suspended Solids (mg/L)	53	1994	2022	-0.72	<0.001	sig
4ABWR002.50	Dissolved Oxygen (mg/L)	179	1994	2024	0.20	0.326	ns
4ABWR002.50	Total Hardness (mg/L)	31	1997	2003	-7.77	0.465	ns
4ABWR002.50	Secchi Depth (m)	164	1994	2024	0.00	0.935	ns
4ABWR002.50	Sulfate (mg/L)	26	1994	2001	2.26	0.052	ns

4ABWR010.55 (Middle Blackwater River - SML)

Station	Variable	Months	First Year	Last Year	Sen's Slope (/decade)	p-value	Sign.
4ABWR010.55	Ammonia (mg/L)	178	1994	2024	-0.01	<0.001	sig
4ABWR010.55	Chloride (mg/L)	26	1994	2001	3.27	0.021	sig
4ABWR010.55	Chlorophyll-*a* (µg/L)	161	1998	2024	1.26	<0.001	sig
4ABWR010.55	*E. coli* (CFU/100 mL)	142	2002	2024	0.00	<0.001	sig
4ABWR010.55	pH (standard units)	176	1994	2024	-0.12	0.007	sig
4ABWR010.55	Temperature (Celsius)	177	1994	2024	1.19	<0.001	sig
4ABWR010.55	Fecal Coliform (CFU/100 mL)	40	1994	2012	0.00	0.007	sig
4ABWR010.55	Nitrogen (mg/L)	177	1994	2024	-0.08	<0.001	sig
4ABWR010.55	NO_x (mg/L)	178	1994	2024	-0.07	<0.001	sig
4ABWR010.55	NO_x + TKN (mg/L)	40	1994	2003	-0.24	0.005	sig
4ABWR010.55	Total Phosphorus (mg/L)	177	1994	2024	-0.00	0.003	sig
4ABWR010.55	Total Orthophosphate (mg/L)	177	1994	2024	0.00	<0.001	sig
4ABWR010.55	Secchi Depth (m)	163	1994	2024	-0.22	<0.001	sig
4ABWR010.55	Sulfate (mg/L)	26	1994	2001	2.85	0.034	sig
4ABWR010.55	Dissolved Oxygen (mg/L)	177	1994	2024	-0.35	0.174	ns
4ABWR010.55	Total Hardness (mg/L)	30	1997	2003	9.36	0.617	ns
4ABWR010.55	Total Kjeldahl Nitrogen (mg/L)	39	1994	2003	-0.04	0.333	ns
4ABWR010.55	Total Suspended Solids (mg/L)	39	1994	2003	0.00	0.681	ns

4ABWR017.42 (Upper Blackwater River - SML)

Station	Variable	Months	First Year	Last Year	Sen's Slope (/decade)	p-value	Sign.
4ABWR017.42	Ammonia (mg/L)	175	1994	2024	-0.01	<0.001	sig
4ABWR017.42	Chloride (mg/L)	23	1994	2001	1.16	0.001	sig
4ABWR017.42	*E. coli* (CFU/100 mL)	141	2002	2024	0.00	<0.001	sig
4ABWR017.42	pH (standard units)	175	1994	2024	-0.18	<0.001	sig
4ABWR017.42	Temperature (Celsius)	175	1994	2024	0.73	0.050	sig
4ABWR017.42	Fecal Coliform (CFU/100 mL)	40	1994	2012	0.00	0.002	sig
4ABWR017.42	Nitrogen (mg/L)	174	1994	2024	-0.04	0.010	sig
4ABWR017.42	NO_x (mg/L)	175	1994	2024	-0.02	0.031	sig
4ABWR017.42	Total Phosphorus (mg/L)	174	1994	2024	0.00	0.047	sig
4ABWR017.42	Total Orthophosphate (mg/L)	174	1994	2024	0.00	<0.001	sig
4ABWR017.42	Sulfate (mg/L)	23	1994	2001	3.37	<0.001	sig
4ABWR017.42	Chlorophyll-*a* (µg/L)	159	1998	2024	1.37	0.054	ns
4ABWR017.42	Dissolved Oxygen (mg/L)	175	1994	2024	-0.18	0.312	ns
4ABWR017.42	Total Hardness (mg/L)	29	1994	2003	1.27	0.910	ns
4ABWR017.42	Total Kjeldahl Nitrogen (mg/L)	36	1994	2003	0.00	0.430	ns
4ABWR017.42	NO_x + TKN (mg/L)	37	1994	2003	0.00	0.774	ns
4ABWR017.42	Secchi Depth (m)	157	1996	2024	0.00	0.996	ns
4ABWR017.42	Total Suspended Solids (mg/L)	36	1994	2003	4.09	0.178	ns

4ABWR045.80 (Rt. 812 Bridge)

Station	Variable	Months	First Year	Last Year	Sen's Slope (/decade)	p-value	Sign.
4ABWR045.80	Ammonia (mg/L)	80	1994	2007	0.00	<0.001	sig
4ABWR045.80	Chloride (mg/L)	65	1997	2024	-0.66	<0.001	sig
4ABWR045.80	Dissolved Oxygen (mg/L)	199	1994	2024	0.42	0.003	sig
4ABWR045.80	*E. coli* (CFU/100 mL)	150	2000	2024	56.00	0.024	sig
4ABWR045.80	pH (standard units)	198	1994	2024	-0.06	0.011	sig
4ABWR045.80	Fecal Coliform (CFU/100 mL)	170	1994	2024	-106.15	<0.001	sig
4ABWR045.80	Total Kjeldahl Nitrogen (mg/L)	144	1994	2024	-0.08	<0.001	sig
4ABWR045.80	Nitrogen (mg/L)	177	1994	2024	-0.06	0.006	sig
4ABWR045.80	NO_x (mg/L)	80	1994	2007	0.13	0.034	sig
4ABWR045.80	Total Phosphorus (mg/L)	176	1994	2024	-0.02	<0.001	sig
4ABWR045.80	Sulfate (mg/L)	65	1997	2024	-0.67	<0.001	sig
4ABWR045.80	Total Suspended Solids (mg/L)	171	1994	2024	-1.01	0.016	sig
4ABWR045.80	Temperature (Celsius)	199	1994	2024	-0.43	0.416	ns
4ABWR045.80	Total Hardness (mg/L)	74	1994	2018	1.66	0.075	ns
4ABWR045.80	NO_x + TKN (mg/L)	53	1994	2003	0.15	0.179	ns
4ABWR045.80	Total Orthophosphate (mg/L)	53	1994	2003	-0.02	0.200	ns

4ACCK001.80 (Mouth Craddock Cr. - SML)

Station	Variable	Months	First Year	Last Year	Sen's Slope (/decade)	p-value	Sign.
4ACCK001.80	Ammonia (mg/L)	180	1994	2024	-0.01	<0.001	sig
4ACCK001.80	Chloride (mg/L)	29	1994	2001	2.59	0.036	sig
4ACCK001.80	Chlorophyll-*a* (µg/L)	164	1998	2024	0.25	0.003	sig
4ACCK001.80	*E. coli* (CFU/100 mL)	143	2002	2024	0.00	<0.001	sig
4ACCK001.80	pH (standard units)	174	1994	2024	-0.14	<0.001	sig
4ACCK001.80	Temperature (Celsius)	179	1994	2024	0.95	0.003	sig
4ACCK001.80	Fecal Coliform (CFU/100 mL)	42	1994	2012	0.00	0.020	sig
4ACCK001.80	Nitrogen (mg/L)	180	1994	2024	-0.08	<0.001	sig
4ACCK001.80	NO_x (mg/L)	180	1994	2024	-0.06	<0.001	sig
4ACCK001.80	NO_x + TKN (mg/L)	41	1994	2003	-0.14	<0.001	sig
4ACCK001.80	Total Phosphorus (mg/L)	180	1994	2024	-0.00	<0.001	sig
4ACCK001.80	Total Orthophosphate (mg/L)	180	1994	2024	0.00	<0.001	sig
4ACCK001.80	Dissolved Oxygen (mg/L)	176	1994	2024	0.08	0.732	ns
4ACCK001.80	Total Hardness (mg/L)	33	1997	2003	-6.21	0.466	ns
4ACCK001.80	Total Kjeldahl Nitrogen (mg/L)	41	1994	2003	0.00	0.508	ns
4ACCK001.80	Secchi Depth (m)	162	1996	2024	0.06	0.258	ns
4ACCK001.80	Sulfate (mg/L)	29	1994	2001	1.56	0.143	ns
4ACCK001.80	Total Suspended Solids (mg/L)	41	1994	2003	0.00	0.064	ns

4ACOA000.60 (Cool Branch – SML)

Station	Variable	Months	First Year	Last Year	Sen's Slope (/decade)	p-value	Sign.
4ACOA000_60	Ammonia (mg/L)	178	1994	2024	-0.01	<0.001	sig
4ACOA000_60	Chloride (mg/L)	26	1994	2001	3.50	0.002	sig
4ACOA000_60	*E. coli* (CFU/100 mL)	142	2002	2024	0.00	<0.001	sig
4ACOA000_60	pH (standard units)	177	1994	2024	-0.13	<0.001	sig
4ACOA000_60	Temperature (Celsius)	178	1994	2024	0.97	<0.001	sig
4ACOA000_60	Fecal Coliform (CFU/100 mL)	42	1994	2012	0.00	0.001	sig
4ACOA000_60	Nitrogen (mg/L)	177	1994	2024	-0.10	<0.001	sig
4ACOA000_60	NO_x (mg/L)	178	1994	2024	-0.06	<0.001	sig
4ACOA000_60	NO_x + TKN (mg/L)	40	1994	2003	-0.14	0.003	sig
4ACOA000_60	Total Phosphorus (mg/L)	177	1994	2024	0.00	<0.001	sig
4ACOA000_60	Total Orthophosphate (mg/L)	178	1994	2024	0.00	<0.001	sig
4ACOA000_60	Sulfate (mg/L)	26	1994	2001	2.33	0.033	sig
4ACOA000_60	Chlorophyll-*a* (µg/L)	162	1998	2024	0.20	0.080	ns
4ACOA000_60	Dissolved Oxygen (mg/L)	178	1994	2024	0.04	0.799	ns
4ACOA000_60	Specific Conductance (µS/cm)	175	1994	2024	-1.56	0.748	ns
4ACOA000_60	Total Hardness (mg/L)	31	1997	2003	-6.00	0.825	ns
4ACOA000_60	Total Kjeldahl Nitrogen (mg/L)	39	1994	2003	-0.02	0.446	ns
4ACOA000_60	Secchi Depth (m)	165	1994	2024	0.05	0.357	ns
4ACOA000_60	Total Suspended Solids (mg/L)	39	1994	2003	-0.83	0.105	ns

4AGIL002.39 (Gills Creek - SML)

Station	Variable	Months	First Year	Last Year	Sen's Slope (/decade)	p-value	Sign.
4AGIL002.39	Ammonia (mg/L)	178	1994	2024	-0.02	<0.001	sig
4AGIL002.39	Chloride (mg/L)	26	1994	2001	5.52	<0.001	sig
4AGIL002.39	Dissolved Oxygen (mg/L)	178	1994	2024	-0.71	0.004	sig
4AGIL002.39	*E. coli* (CFU/100 mL)	143	2002	2024	0.00	<0.001	sig
4AGIL002.39	pH (standard units)	177	1994	2024	-0.22	<0.001	sig
4AGIL002.39	Fecal Coliform (CFU/100 mL)	42	1994	2012	0.00	0.011	sig
4AGIL002.39	Nitrogen (mg/L)	177	1994	2024	-0.06	<0.001	sig
4AGIL002.39	NO_x (mg/L)	178	1994	2024	-0.03	<0.001	sig
4AGIL002.39	Total Phosphorus (mg/L)	177	1994	2024	-0.00	<0.001	sig
4AGIL002.39	Total Orthophosphate (mg/L)	177	1994	2024	0.00	<0.001	sig
4AGIL002.39	Secchi Depth (m)	161	1994	2024	-0.10	0.038	sig
4AGIL002.39	Sulfate (mg/L)	26	1994	2001	5.19	<0.001	sig
4AGIL002.39	Chlorophyll-*a* (µg/L)	161	1998	2024	0.47	0.071	ns
4AGIL002.39	Temperature (Celsius)	178	1994	2024	0.53	0.117	ns
4AGIL002.39	Total Hardness (mg/L)	30	1997	2003	-1.03	0.972	ns
4AGIL002.39	Total Kjeldahl Nitrogen (mg/L)	39	1994	2003	0.00	0.717	ns
4AGIL002.39	NO_x + TKN (mg/L)	40	1994	2003	-0.06	0.079	ns
4AGIL002.39	Total Suspended Solids (mg/L)	39	1994	2003	0.00	0.952	ns

4AGIL008.30 (Rt. 834 Bridge, near Booker T. Washington National Monument)

Station	Variable	Months	First Year	Last Year	Sen's Slope (/decade)	p-value	Sign.
4AGIL008.30	Ammonia (mg/L)	48	1994	2024	-0.02	0.020	sig
4AGIL008.30	Dissolved Oxygen (mg/L)	68	1994	2024	1.26	0.004	sig
4AGIL008.30	Fecal Coliform (CFU/100 mL)	43	1994	2024	-956.46	<0.001	sig
4AGIL008.30	Total Suspended Solids (mg/L)	30	1994	2024	-5.58	0.023	sig
4AGIL008.30	Chlorophyll-*a* (µg/L)	9	2001	2024	0.91	0.211	ns
4AGIL008.30	*E. coli* (CFU/100 mL)	42	2000	2024	36.18	0.455	ns
4AGIL008.30	pH (standard units)	68	1994	2024	-0.21	0.069	ns
4AGIL008.30	Temperature (Celsius)	68	1994	2024	-2.09	0.195	ns
4AGIL008.30	Total Kjeldahl Nitrogen (mg/L)	43	1994	2024	-0.07	0.112	ns
4AGIL008.30	Nitrogen (mg/L)	67	1994	2024	-0.05	0.426	ns
4AGIL008.30	NO_x (mg/L)	48	1994	2024	-0.02	0.702	ns
4AGIL008.30	NO_x + TKN (mg/L)	43	1994	2024	-0.08	0.281	ns
4AGIL008.30	Total Phosphorus (mg/L)	67	1994	2024	-0.01	0.238	ns
4AGIL008.30	Total Orthophosphate (mg/L)	43	1994	2024	-0.01	0.152	ns

4AROA158.22 (Dam - SML)

Station	Variable	Months	First Year	Last Year	Sen's Slope (/decade)	p-value	Sign.
4AROA158.22	Ammonia (mg/L)	182	1994	2024	-0.01	<0.001	sig
4AROA158.22	Chloride (mg/L)	29	1994	2001	3.46	0.012	sig
4AROA158.22	Chlorophyll-*a* (µg/L)	166	1998	2024	0.27	0.009	sig
4AROA158.22	*E. coli* (CFU/100 mL)	143	2002	2024	0.00	<0.001	sig
4AROA158.22	pH (standard units)	176	1994	2024	-0.16	<0.001	sig
4AROA158.22	Temperature (Celsius)	181	1994	2024	1.25	<0.001	sig
4AROA158.22	Fecal Coliform (CFU/100 mL)	40	1994	2012	0.00	0.043	sig
4AROA158.22	Total Hardness (mg/L)	33	1997	2003	-16.05	0.019	sig
4AROA158.22	Nitrogen (mg/L)	182	1994	2024	-0.09	<0.001	sig
4AROA158.22	NO_x (mg/L)	182	1994	2024	-0.06	<0.001	sig
4AROA158.22	NO_x + TKN (mg/L)	41	1994	2003	-0.15	0.015	sig
4AROA158.22	Total Phosphorus (mg/L)	182	1994	2024	-0.00	<0.001	sig
4AROA158.22	Total Orthophosphate (mg/L)	182	1994	2024	0.00	<0.001	sig
4AROA158.22	Total Suspended Solids (mg/L)	41	1994	2003	-1.54	<0.001	sig
4AROA158.22	Dissolved Oxygen (mg/L)	178	1994	2024	0.10	0.639	ns
4AROA158.22	Total Kjeldahl Nitrogen (mg/L)	41	1994	2003	0.00	0.686	ns
4AROA158.22	Secchi Depth (m)	163	1996	2024	0.00	0.845	ns
4AROA158.22	Sulfate (mg/L)	29	1994	2001	0.98	0.399	ns

4AROA163.76 (Confluence with Blackwater River - SML)

Station	Variable	Months	First Year	Last Year	Sen's Slope (/decade)	p-value	Sign.
4AROA163.76	Ammonia (mg/L)	183	1994	2024	-0.01	<0.001	sig
4AROA163.76	Chloride (mg/L)	30	1994	2001	3.38	0.019	sig
4AROA163.76	Chlorophyll-*a* (µg/L)	165	1998	2024	0.27	0.023	sig
4AROA163.76	*E. coli* (CFU/100 mL)	144	2002	2024	0.00	<0.001	sig
4AROA163.76	pH (standard units)	177	1994	2024	-0.10	0.007	sig
4AROA163.76	Temperature (Celsius)	182	1994	2024	1.39	<0.001	sig
4AROA163.76	Fecal Coliform (CFU/100 mL)	43	1994	2012	0.00	0.046	sig
4AROA163.76	Total Kjeldahl Nitrogen (mg/L)	56	1994	2022	-0.02	0.005	sig
4AROA163.76	Nitrogen (mg/L)	183	1994	2024	-0.07	<0.001	sig
4AROA163.76	NO_x (mg/L)	175	1994	2024	-0.05	<0.001	sig
4AROA163.76	Total Phosphorus (mg/L)	183	1994	2024	0.00	<0.001	sig
4AROA163.76	Total Orthophosphate (mg/L)	175	1994	2024	0.00	<0.001	sig
4AROA163.76	Total Suspended Solids (mg/L)	56	1994	2022	-0.42	<0.001	sig
4AROA163.76	Dissolved Oxygen (mg/L)	179	1994	2024	0.26	0.196	ns
4AROA163.76	Total Hardness (mg/L)	34	1997	2003	1.26	0.756	ns
4AROA163.76	NO_x + TKN (mg/L)	42	1994	2003	-0.12	0.052	ns
4AROA163.76	Secchi Depth (m)	162	1996	2024	0.00	0.685	ns
4AROA163.76	Sulfate (mg/L)	30	1994	2001	2.61	0.084	ns

4AROA167.34 (Buoy R12 - SML)

Station	Variable	Months	First Year	Last Year	Sen's Slope (/decade)	p-value	Sign.
4AROA167.34	Ammonia (mg/L)	182	1994	2024	-0.01	<0.001	sig
4AROA167.34	Chloride (mg/L)	30	1994	2001	3.56	0.004	sig
4AROA167.34	Dissolved Oxygen (mg/L)	178	1994	2024	0.50	0.025	sig
4AROA167.34	*E. coli* (CFU/100 mL)	144	2002	2024	0.00	<0.001	sig
4AROA167.34	pH (standard units)	176	1994	2024	-0.15	<0.001	sig
4AROA167.34	Temperature (Celsius)	181	1994	2024	1.32	<0.001	sig
4AROA167.34	Fecal Coliform (CFU/100 mL)	43	1994	2012	0.00	0.021	sig
4AROA167.34	Total Hardness (mg/L)	34	1997	2003	-33.50	<0.001	sig
4AROA167.34	Nitrogen (mg/L)	182	1994	2024	-0.10	<0.001	sig
4AROA167.34	NO_x (mg/L)	182	1994	2024	-0.07	<0.001	sig
4AROA167.34	Total Phosphorus (mg/L)	182	1994	2024	-0.00	<0.001	sig
4AROA167.34	Total Orthophosphate (mg/L)	182	1994	2024	0.00	<0.001	sig
4AROA167.34	Chlorophyll-*a* (µg/L)	164	1998	2024	0.16	0.315	ns
4AROA167.34	Total Kjeldahl Nitrogen (mg/L)	42	1994	2003	0.00	0.626	ns
4AROA167.34	NO_x + TKN (mg/L)	42	1994	2003	-0.15	0.052	ns
4AROA167.34	Secchi Depth (m)	164	1996	2024	0.00	0.927	ns
4AROA167.34	Sulfate (mg/L)	30	1994	2001	1.25	0.432	ns
4AROA167.34	Total Suspended Solids (mg/L)	42	1994	2003	0.00	0.186	ns

4AROA175.63 (Hales Ford - SML)

Station	Variable	Months	First Year	Last Year	Sen's Slope (/decade)	p-value	Sign.
4AROA175.63	Ammonia (mg/L)	186	1994	2024	-0.02	<0.001	sig
4AROA175.63	Chloride (mg/L)	31	1994	2001	5.92	0.003	sig
4AROA175.63	Chlorophyll-*a* (µg/L)	167	1998	2024	1.23	<0.001	sig
4AROA175.63	*E. coli* (CFU/100 mL)	152	2002	2024	0.00	<0.001	sig
4AROA175.63	pH (standard units)	185	1994	2024	-0.18	<0.001	sig
4AROA175.63	Temperature (Celsius)	186	1994	2024	0.97	0.002	sig
4AROA175.63	Fecal Coliform (CFU/100 mL)	42	1994	2012	0.00	0.001	sig
4AROA175.63	Total Hardness (mg/L)	34	1997	2003	-42.21	0.013	sig
4AROA175.63	Nitrogen (mg/L)	186	1994	2024	-0.08	<0.001	sig
4AROA175.63	NO_x (mg/L)	178	1994	2024	-0.04	0.023	sig
4AROA175.63	Total Phosphorus (mg/L)	186	1994	2024	-0.00	<0.001	sig
4AROA175.63	Total Orthophosphate (mg/L)	178	1994	2024	0.00	0.009	sig
4AROA175.63	Dissolved Oxygen (mg/L)	183	1994	2024	0.31	0.206	ns
4AROA175.63	Total Kjeldahl Nitrogen (mg/L)	56	1994	2022	-0.02	0.182	ns
4AROA175.63	NO_x + TKN (mg/L)	43	1994	2003	-0.13	0.391	ns
4AROA175.63	Secchi Depth (m)	168	1994	2024	0.00	0.297	ns
4AROA175.63	Sulfate (mg/L)	31	1994	2001	1.21	0.646	ns
4AROA175.63	Total Suspended Solids (mg/L)	56	1994	2022	-0.48	0.057	ns

4AROA180.21 (Confluence with Indian Cr. - SML)

Station	Variable	Months	First Year	Last Year	Sen's Slope (/decade)	p-value	Sign.
4AROA180.21	Ammonia (mg/L)	186	1994	2024	-0.03	<0.001	sig
4AROA180.21	Chloride (mg/L)	31	1994	2001	8.00	<0.001	sig
4AROA180.21	Chlorophyll-*a* (µg/L)	166	1998	2024	1.23	0.023	sig
4AROA180.21	*E. coli* (CFU/100 mL)	152	2002	2024	0.00	<0.001	sig
4AROA180.21	pH (standard units)	186	1994	2024	-0.17	<0.001	sig
4AROA180.21	Temperature (Celsius)	187	1994	2024	0.81	0.012	sig
4AROA180.21	Fecal Coliform (CFU/100 mL)	42	1994	2012	0.00	0.002	sig
4AROA180.21	Total Hardness (mg/L)	34	1997	2003	-45.43	<0.001	sig
4AROA180.21	Nitrogen (mg/L)	186	1994	2024	-0.08	<0.001	sig
4AROA180.21	NO_x (mg/L)	186	1994	2024	-0.04	0.048	sig
4AROA180.21	Total Phosphorus (mg/L)	186	1994	2024	-0.00	<0.001	sig
4AROA180.21	Total Orthophosphate (mg/L)	186	1994	2024	-0.00	<0.001	sig
4AROA180.21	Dissolved Oxygen (mg/L)	186	1994	2024	0.09	0.719	ns
4AROA180.21	Total Kjeldahl Nitrogen (mg/L)	43	1994	2003	0.00	0.942	ns
4AROA180.21	NO_x + TKN (mg/L)	43	1994	2003	-0.05	0.714	ns
4AROA180.21	Secchi Depth (m)	165	1994	2024	0.00	0.321	ns
4AROA180.21	Sulfate (mg/L)	31	1994	2001	4.42	0.083	ns
4AROA180.21	Total Suspended Solids (mg/L)	42	1994	2003	0.00	0.931	ns

4AROA183.64 (Confluence with Beaverdam Cr. - SML)

Station	Variable	Months	First Year	Last Year	Sen's Slope (/decade)	p-value	Sign.
4AROA183.64	Ammonia (mg/L)	186	1994	2024	-0.03	<0.001	sig
4AROA183.64	Chloride (mg/L)	30	1994	2001	7.58	<0.001	sig
4AROA183.64	*E. coli* (CFU/100 mL)	150	2002	2024	0.00	<0.001	sig
4AROA183.64	pH (standard units)	186	1994	2024	-0.16	<0.001	sig
4AROA183.64	Temperature (Celsius)	187	1994	2024	0.94	0.004	sig
4AROA183.64	Fecal Coliform (CFU/100 mL)	42	1994	2012	0.00	0.001	sig
4AROA183.64	Nitrogen (mg/L)	186	1994	2024	-0.08	0.001	sig
4AROA183.64	Total Phosphorus (mg/L)	186	1994	2024	-0.00	<0.001	sig
4AROA183.64	Total Orthophosphate (mg/L)	186	1994	2024	0.00	<0.001	sig
4AROA183.64	Chlorophyll-*a* (µg/L)	167	1998	2024	0.77	0.262	ns
4AROA183.64	Dissolved Oxygen (mg/L)	186	1994	2024	0.31	0.214	ns
4AROA183.64	Total Hardness (mg/L)	34	1997	2003	-6.67	0.733	ns
4AROA183.64	Total Kjeldahl Nitrogen (mg/L)	43	1994	2003	0.10	0.310	ns
4AROA183.64	NO_x (mg/L)	186	1994	2024	-0.03	0.182	ns
4AROA183.64	NO_x + TKN (mg/L)	43	1994	2003	0.14	0.530	ns
4AROA183.64	Secchi Depth (m)	165	1994	2024	-0.07	0.084	ns
4AROA183.64	Sulfate (mg/L)	30	1994	2001	4.19	0.080	ns
4AROA183.64	Total Suspended Solids (mg/L)	41	1994	2003	0.87	0.678	ns

4AROA192.94 (Hardy Ford - SML)

Station	Variable	Months	First Year	Last Year	Sen's Slope (/decade)	p-value	Sign.
4AROA192.94	Ammonia (mg/L)	186	1994	2024	-0.01	0.002	sig
4AROA192.94	Chloride (mg/L)	31	1994	2001	14.32	0.007	sig
4AROA192.94	Chlorophyll-*a* (µg/L)	166	1998	2024	-1.18	<0.001	sig
4AROA192.94	pH (standard units)	186	1994	2024	-0.13	<0.001	sig
4AROA192.94	Fecal Coliform (CFU/100 mL)	42	1994	2012	0.00	<0.001	sig
4AROA192.94	NO_x (mg/L)	186	1994	2024	0.11	0.012	sig
4AROA192.94	NO_x + TKN (mg/L)	43	1994	2003	0.99	0.004	sig
4AROA192.94	Total Phosphorus (mg/L)	186	1994	2024	-0.01	<0.001	sig
4AROA192.94	Total Orthophosphate (mg/L)	186	1994	2024	0.00	<0.001	sig
4AROA192.94	Secchi Depth (m)	165	1994	2024	0.07	0.001	sig
4AROA192.94	Dissolved Oxygen (mg/L)	186	1994	2024	-0.24	0.061	ns
4AROA192.94	*E. coli* (CFU/100 mL)	152	2002	2024	0.00	0.115	ns
4AROA192.94	Temperature (Celsius)	187	1994	2024	0.05	0.907	ns
4AROA192.94	Total Hardness (mg/L)	34	1997	2003	9.99	0.722	ns
4AROA192.94	Total Kjeldahl Nitrogen (mg/L)	43	1994	2003	-0.19	0.109	ns
4AROA192.94	Nitrogen (mg/L)	186	1994	2024	-0.01	0.783	ns
4AROA192.94	Sulfate (mg/L)	31	1994	2001	1.99	0.646	ns
4AROA192.94	Total Suspended Solids (mg/L)	42	1994	2003	0.00	0.530	ns

4AROA199.20 (Blue Ridge Parkway Bridge, Below Roanoke)

Station	Variable	Months	First Year	Last Year	Sen's Slope (/decade)	p-value	Sign.
4AROA199.20	pH (standard units)	90	2005	2024	0.19	<0.001	sig
4AROA199.20	Ammonia (mg/L)	16	2005	2022	0.01	0.653	ns
4AROA199.20	Dissolved Oxygen (mg/L)	89	2005	2024	-0.12	0.625	ns
4AROA199.20	*E. coli* (CFU/100 mL)	87	2005	2024	14.89	0.231	ns
4AROA199.20	Temperature (Celsius)	91	2005	2024	1.04	0.397	ns
4AROA199.20	Fecal Coliform (CFU/100 mL)	79	2009	2024	0.00	0.414	ns
4AROA199.20	Total Hardness (mg/L)	43	2015	2024	17.74	0.225	ns
4AROA199.20	Total Kjeldahl Nitrogen (mg/L)	78	2009	2024	0.00	0.685	ns
4AROA199.20	Nitrogen (mg/L)	88	2005	2024	-0.06	0.790	ns
4AROA199.20	NO_x (mg/L)	16	2005	2022	-0.02	1.000	ns
4AROA199.20	Total Phosphorus (mg/L)	87	2005	2024	0.00	0.886	ns
4AROA199.20	Total Suspended Solids (mg/L)	91	2005	2024	0.00	0.875	ns

4AWTH000.40 (Mouth of Witcher Cr. - SML)

Station	Variable	Months	First Year	Last Year	Sen's Slope (/decade)	p-value	Sign.
4AWTH000.40	Ammonia (mg/L)	182	1994	2024	-0.01	<0.001	sig
4AWTH000.40	Chlorophyll-*a* (µg/L)	166	1998	2024	0.36	<0.001	sig
4AWTH000.40	*E. coli* (CFU/100 mL)	144	2002	2024	0.00	<0.001	sig
4AWTH000.40	pH (standard units)	176	1994	2024	-0.11	<0.001	sig
4AWTH000.40	Temperature (Celsius)	181	1994	2024	0.94	<0.001	sig
4AWTH000.40	Fecal Coliform (CFU/100 mL)	42	1994	2012	0.00	0.007	sig
4AWTH000.40	Nitrogen (mg/L)	182	1994	2024	-0.08	<0.001	sig
4AWTH000.40	NO_x (mg/L)	182	1994	2024	-0.06	<0.001	sig
4AWTH000.40	Total Phosphorus (mg/L)	182	1994	2024	0.00	<0.001	sig
4AWTH000.40	Total Orthophosphate (mg/L)	182	1994	2024	0.00	<0.001	sig
4AWTH000.40	Secchi Depth (m)	162	1996	2024	0.13	0.044	sig
4AWTH000.40	Chloride (mg/L)	29	1994	2001	3.00	0.091	ns
4AWTH000.40	Dissolved Oxygen (mg/L)	178	1994	2024	0.13	0.513	ns
4AWTH000.40	Total Hardness (mg/L)	33	1997	2003	-8.38	0.145	ns
4AWTH000.40	Total Kjeldahl Nitrogen (mg/L)	41	1994	2003	0.00	0.598	ns
4AWTH000.40	NO_x + TKN (mg/L)	41	1994	2003	-0.12	0.052	ns
4AWTH000.40	Sulfate (mg/L)	29	1994	2001	1.10	0.464	ns
4AWTH000.40	Total Suspended Solids (mg/L)	41	1994	2003	0.00	0.076	ns

Appendix E: SWAT Model Development

We configured and calibrated SWAT models for each basin. Model inputs included high-resolution soil data from the Soil Survey Geographic Database (SSURGO), land cover data from the National Land Cover Database (NLCD), and daily precipitation and temperature records from Parameter-elevation Regressions on Independent Slopes Model (PRISM). Calibration was implemented using the Sequential Uncertainty Fitting, version 2 (SUFI-2) algorithm in SWAT Calibration and Uncertainty Programs (SWAT-CUP) for the period 2001–2012, with independent validation for 2013–2024. Model performance was quantified using Nash–Sutcliffe Efficiency (NSE), percent bias (PBIAS), and coefficient of determination (R^2).

SWAT Model Input

To support SWAT model configuration and simulation, several spatial and temporal input datasets were compiled for the SML watershed. Land cover information was obtained from the 2011 NLCD. The digital elevation model (DEM) data were downloaded from The National Map (TNM) of the USGS. The 30-m resolution DEM was used for watershed delineation, stream network generation, and slope calculations important for hydrologic and water quality modeling.

Soil data were acquired from the SSURGO database by the USDA Natural Resources Conservation Service. This high-resolution dataset provides detailed spatial attributes such as soil texture, available water content, saturated hydraulic conductivity, and bulk density, which can be mapped to the SWAT soil parameter structure as model input. Daily weather data, including precipitation and minimum/maximum temperatures, were downloaded from the PRISM Climate Group for the period 1999-01-01 to 2024-12-31. These gridded climate datasets were spatially linked to the centroids of each subbasin to generate the required weather inputs for the SWAT model. Observed streamflow data were obtained from two USGS gauge stations, USGS 02056900 (Blackwater River near Rocky Mount, VA) and USGS 02056000 (Roanoke River at Niagara, VA), representing the Blackwater and Roanoke River Basins, respectively. These are the only available long-term streamflow gauges within the two basins, and their daily discharge records provided essential observations for calibrating and validating the simulated hydrologic outputs in the SWAT model.

SWAT Model Configuration

Separate SWAT models were developed for the Blackwater River and Roanoke River Basins to account for their distinct watershed characteristics and land-use patterns. We used ArcSWAT 2012 to simulate streamflow and water quality. Watershed delineation was performed using the 30-meter resolution DEM, with a minimum threshold drainage area of 1000 hectares. Additionally, we manually added outlets for locations of USGS gauge stations (described above). Watershed delineation resulted in the division of the Blackwater Basin into 17 subbasins[5] and the Roanoke River Basin into 10 subbasins.

[5] In the SWAT model, a subbasin is a spatially defined area within a watershed that is based on topographic criteria and connected to a river channel. The SWAT subbasins are computational units defined by the modeler.

Hydrologic Response Units[6] (HRUs) were defined using a multiple-threshold approach, applying 10% thresholds for land use, soil type, and slope class. This method minimized the influence of very small land use or soil units, consistent with recommendations by FitzHugh and Mackay (2000). The entire delineation process generated Geographic Information System (GIS) layers for subbasins, stream reaches, and elevation profiles, as well as detailed topographic summary reports. Daily precipitation, and minimum and maximum temperatures, were imported from the PRISM dataset for the period 1999–2024. Additional meteorological variables such as wind speed, solar radiation, and relative humidity were populated using SWAT default values where observational data were not available.

SWAT Model Calibration

Model calibration and validation were performed using SWAT-CUP with the SUFI-2 algorithm. The SUFI-2 provides an efficient, probabilistic framework for optimizing model parameters while simultaneously quantifying uncertainty associated with input data, parameter ranges, and model structure. The calibration process involved adjusting parameter values within predefined bounds to minimize discrepancies between observed and simulated streamflow. A total of ten key parameters, commonly used in SWAT hydrologic calibration, were selected based on their known sensitivity and influence on flow processes. Table E-1 lists these parameters along with brief descriptions of their general impact on streamflow dynamics.

Table E-1. Descriptions of Calibrated SWAT Parameters.

Parameter	Description
CN2	Runoff curve number; affects infiltration vs. runoff
ESCO	Controls soil evaporation depth
SURLAG	Surface runoff lag time (days)
ALPHA_BF	Baseflow recession rate (1/day)
GWQMN	Threshold aquifer water depth for baseflow (mm)
RCHRG_DP	Fraction of water percolating to deep aquifer
GW_DELAY	Time lag between recharge and baseflow (days)
GW_REVAP	Upward movement of water from aquifer to soil
SOL_AWC	Plant available water content in soil (fraction)
SOL_K	Saturated hydraulic conductivity (mm/hr)

Daily streamflow was calibrated over a 12-year period (2001–2012) and validated using a separate 12-year period (2013–2024) to ensure model robustness. Streamflow calibration focused on replicating both baseflow and storm flow dynamics, essential for estimating sediment and nutrient yields. Model performance was evaluated using three statistical metrics recommended by Moriasi et al. (2007): Nash-Sutcliffe Efficiency (NSE), Percent Bias (PBIAS), and Coefficient of Determination (R^2). Nash-Sutcliffe Efficiency is commonly used in assessing hydrological model performance by comparing residual variance with the observed data variance. Values range from $-\infty$ to 1.0, with NSE > 0.50 considered acceptable for daily flow calibration. The PBIAS measures the average tendency of the simulated data to be larger or

[6] Subbasins are divided into Hydrologic Response Units (HRUs). Sub-basins are the main components of the watershed, while HRUs are the fundamental spatial units within them.

smaller than their observed counterparts. Negative values indicate overestimation, while positive values indicate underestimation. Acceptable bias thresholds are typically ±25% for streamflow.

SWAT-CUP Calibration and Validation

The calibration and validation statistics for both basins are summarized in Table E-2. For the Blackwater River Basin, SWAT-CUP calibration was performed using 1,000 simulations, with NSE as the objective function. Multiple iterations were required to refine parameter ranges and improve model fit. The best simulation achieved an NSE of 0.61 and an R^2 of 0.62 during the calibration period (2001–2012), indicating satisfactory performance in simulating daily streamflow. Additional metrics included a PBIAS of 7.5%, suggesting a slight underestimation of flow. Model validation was conducted over the period 2013–2024, resulting in an NSE of 0.52, R^2 of 0.60, and a PBIAS of –11.9%, indicating moderate overestimation but still within acceptable thresholds for hydrologic modeling. The shift in PBIAS sign between periods reflects the model's sensitivity to changing conditions and input variability, a common occurrence in long-term watershed modeling.

For the Roanoke River basin, calibration results yielded an NSE of 0.57, R^2 of 0.59, and a PBIAS of 5.2%, reflecting a reasonable match between observed and simulated flows. Validation performance remained within acceptable thresholds, with an NSE of 0.50, R^2 of 0.53, and PBIAS of 3.39%, indicating slight underestimation during the later simulation period.

Table E-2. SWAT-CUP Calibration and Validation Performance Metrics for Daily Streamflow in the Blackwater and Roanoke River Basins.

Daily streamflow	Calibration (2001-2012)			Validation (2013-2024)		
	NSE	R^2	PBIAS	NSE	R^2	PBIAS
Blackwater River Basin	0.61	0.62	7.5%	0.52	0.60	-11.9%
Roanoke River Basin	0.57	0.59	5.2%	0.50	0.53	3.39%

Table E-3 presents the best-fitted values for ten key SWAT parameters calibrated using SUFI-2 in SWAT-CUP for the Blackwater and Roanoke River basins. These calibrated values highlight important hydrologic differences between the two basins. For instance, the larger adjustment in curve number (r_CN2 = –0.297) in the Blackwater basin indicates a greater reduction in surface runoff potential compared to the Roanoke basin (r_CN2 = –0.185), likely reflecting the higher proportion of forest cover. The higher SURLAG (surface runoff lag time) and GW_DELAY values in the Blackwater basin also point to a slower hydrologic response and delayed groundwater contributions, consistent with its steeper, forested topography. In contrast, the Roanoke basin exhibits higher deep aquifer recharge (v_RCHRG_DP = 0.832) and slightly greater soil water holding capacity (v_SOL_AWC = 0.221), which are indicative of its more urbanized and valley-dominated landscape. These parameter variations contribute to more accurate, basin-specific simulation of flow dynamics.

Table E-3. SWAT Parameters Calibration for Blackwater and Roanoke River Basins Using SUFI-2 in SWAT-CUP.

Parameter	Units	Calibration Range	Blackwater	Roanoke
r_CN2	Unitless	-30% to 30%	-29.7%	-18.5%
v_ESCO	Unitless	0 to 1.0	0.78	0.487
v_SURLAG	Days	1 to 10	3.252	1.288
v_ALPHA_BF	$Days^{-1}$ (1/day)	0.1 to 1.0	0.454	0.124
v_GWQMN	mm	0 to 500	291.807	216.622
v_RCHRG_DP	Fraction (unitless)	0 to 1.0	0.611	0.832
v_GW_DELAY	Days	1 to 450	69.142	30.859
v_GW_REVAP	Unitless	0.02 to 0.2	0.1	0.073
v_SOL_AWC	mm H_2O/mm soil	0 to 0.3	0.201	0.221
v_SOL_K	mm/hr	0.5 to 150	45.934	48.674

Appendix E Reference

FitzHugh, T. W., & Mackay, D. S. (2000). Impacts of input parameter spatial aggregation on an agricultural nonpoint source pollution model. *Journal of Hydrology* 236 (1). 35-53. doi:10.1016/s0022-1694(00)00276-6