Improving Learning and Science Outcomes in The Reservoir Observer Student Scientists (ROSS) Program Through Reflection and Skill Building Exercises

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Abstract

The Reservoir Observer Student Scientists (ROSS) program engages high school students in year-round water quality monitoring to detect and understand cyanobacterial harmful algal blooms (cyanoHABs). This place-based participatory science program combines hands-on sampling, data analysis, and reflective learning to foster scientific literacy and contribute to environmental research. A mid-year data quality and analysis activity was introduced to improve students' understanding of sampling rigor and enhance the reliability of their contributions. Additional points of reflection at the end of the school year improved students' understanding of limnology and the process of doing science. Results show that students not only developed procedural knowledge and data literacy but also produced scientifically valid data, comparable to professional standards. The program demonstrates how structured training and inquiry-based activities can simultaneously advance educational outcomes and support long-term ecological monitoring.

Coversheet Statement

1 Introduction

The Reservoir Observer Student Scientists (ROSS) program is a place-based, participatory science program that trains high school students to monitor the health of local lakes and reservoirs. Participatory Science programs, such as ROSS, not only generate valuable scientific data, but also foster learning outcomes such as increased scientific knowledge, data literacy skills, and self-efficacy, particularly among youth (Ballard et al., 2017; Bonney et al., 2009; Shirk et al., 2012). In a formal education setting, participatory science offers a promising pathway to engage students in meaningful STEM experiences. Through hands-on sampling and data analysis, students in the ROSS program contribute to ongoing research on cyanobacterial harmful algal blooms (cyanoHABs), an increasingly prevalent environmental concern that threatens water quality, public health, and local economies. CyanoHABs can produce toxic secondary metabolites, including cyanotoxins and taste-and-odor compounds, that impair water use for recreation and drinking (Watson et al., 2015), leading to economic loss from increased drinking water treatment costs, decreased property values, and recreational closures (Dodds et al., 2009).

The ROSS program addresses a critical gap in water quality monitoring: the under-sampling of lakes during the shoulder and winter seasons. Academic and governmental monitoring efforts often focus on summer months, leaving seasonal dynamics of cyanoHABs poorly understood (Hampton et al., 2017). By engaging students in weekly sampling across the academic year, ROSS extends the temporal resolution of monitoring and produces data that can guide management decisions and advance scientific insight into bloom development, toxin production, and seasonal patterns. It also offers students expanded learning experiences that build data literacy and support the development of a strong science identity. While ROSS provides students with hands-on experience in limnology, ensuring the scientific validity of student-collected data remains a central challenge.

To address this, we expanded ROSS hands-on training on water sample collection and processing to include structured learning sessions combined with data analysis and quality assessment activities. Additionally, a reflection questionnaire was introduced at the end of the school year to assess students' learning outcomes. We aim to (1) understand whether extended training improves the scientific validity and reproducibility of student-collected water quality data relative to professional quality control standards, and (2) assess whether structured data-quality activities and assessments enhance students' limnological understanding, data literacy, and scientific identity. We hypothesize that the extended training significantly impacts both the scientific validity of student-collected data and students' understanding of scientific limnological concepts.

2 Literature Review

Participatory science programs offer dual benefits: they generate valuable scientific data and provide meaningful learning experiences for participants (Bonney et al., 2009; Shirk et al., 2012). These programs are particularly impactful for youth, who gain scientific knowledge, process skills, and increased self-efficacy through authentic STEM experiences (Ballard et al., 2017; National Academies of Sciences, Engineering, and Medicine, 2018). As STEM disciplines increasingly prioritize equity and inclusion, participatory science provides a mechanism to engage diverse student populations in real-world science (Fischer and Wentz, 2020).

Participatory science has emerged as a valuable approach for expanding the spatial and temporal scope of environmental monitoring, particularly in aquatic ecosystems. Water quality monitoring programs often face logistical and financial constraints that limit their ability to collect data year-round or across diverse geographic regions. Participatory science helps overcome these limitations by engaging participants, including students, in systematic data collection efforts that complement professional research (Bonney et al., 2016; Brossard et al., 2005). A common concern in participatory science is the reliability of data collected by non-professionals. However, research consistently shows that with proper training and support, participants, including high school students, can produce data of comparable quality to that of professionals (Albus et al., 2019; Fischer et al., 2021; Lewandowski and Specht, 2015). Structured training, clear protocols, and opportunities for reflection are key to ensuring good data quality. Kobori et al. (2016) and Vohland et al. (2021) emphasize that training not only improves data accuracy but also enhances volunteer engagement and retention.

In freshwater systems, participatory science has been instrumental in detecting harmful algal blooms (HABs), tracking nutrient pollution, and identifying long-term ecological trends. Programs such as the Lakes of Missouri Volunteer Program (LMVP), the Phytoplankton Monitoring Network (PMN), and FreshWater Watch have demonstrated that citizen science can yield scientifically robust data when volunteers are properly trained and supported (Obrecht et al., 1998). These initiatives have shown that with clear protocols, consistent methodologies, and rigorous quality assurance measures, non-professional participants can collect water quality data that are comparable in accuracy and reliability to those gathered by professional scientists. For example, the PMN has contributed to early detection of harmful algal blooms in coastal regions (Batten et al., 2019), with volunteer data informing public health advisories and environmental management decisions. Similarly, LMVP has built a long-term dataset (North et al., 2025a) that supports research on eutrophication and lake health across Missouri, while FreshWater Watch has enabled global-scale monitoring of freshwater ecosystems through standardized sampling and cloud-based data sharing. These programs underscore the potential of participatory science to expand the spatial and temporal reach of environmental monitoring and produce data that meet scientific standards when embedded within well-designed training and validation frameworks (Lewandowski and Specht, 2015; Kobori et al., 2016).

Participatory science has emerged as a powerful approach for youth by involving them directly in authentic scientific inquiry and supporting their scientific literacy. Youth-focused participatory science programs have been shown to foster participants' capacity to understand and act on environmental knowledge (Ballard et al., 2017). To realize the full educational potential of participatory science in classrooms, projects must be intentionally designed for school contexts. The School-Based Participatory Science (SBPS) framework (Smith et al., 2025) articulates four key principles for effective classroom integration: attending to classroom context, building teacher capacity, designing projects that fit instructional goals, and prioritizing meaningful student experience. These principles highlight how well-designed participatory science experiences do more than engage students; they create authentic conditions in which learners can develop essential competencies such as data literacy.

Data literacy is supported by developing skills such as identifying problems, framing questions, analyzing data, and making evidence-based decisions (Gummer and Mandinach, 2015). As Mandinach and Gummer (2016) argue, these abilities should be integrated into everyday science instruction rather than treated as standalone skills. Embedding data-quality instruction within science curricula further strengthens students' ability to evaluate evidence and understand the consequences of methodological choices (Mandinach and Gummer, 2016; Hamilton et al., 2009). Inquiry-Based Science Education supports this integration by engaging students in hands-on, reflective investigations, and research shows that working with "messy" real-world data strengthens analytical skills and fosters a deeper appreciation of scientific uncertainty (Montana State University, 2023).

Involving students directly in data interpretation and decision-making further supports the development of robust data literacy (Hamilton et al., 2009; National Center for Education Statistics, 2018). Place-based education approaches extend these benefits by helping students situate abstract scientific ideas within relevant local environmental contexts (Cho et al., 2021; Semken et al., 2017; Haywood et al., 2021).

Participatory science provides an ideal structure for integrating data literacy practices into classroom science. Because students collect, interpret, and evaluate real data using standardized protocols, participatory science inherently engages them in the core components of data literacy—framing questions, applying evidence-based reasoning, and critically assessing data quality. In classroom settings, this work becomes consequential rather than hypothetical; students' decisions directly influence the reliability and utility of the datasets they help produce. The SBPS framework illustrates how participatory science can be purposefully aligned with instructional goals by emphasizing project design, contextual fit, and meaningful student participation (Smith et al., 2025). When these principles are enacted, participatory science offers structured opportunities for students to practice data documentation, quality control, and interpretation—elements often missing from traditional science activities. In this way, participatory science fills a critical gap in science education by providing an authentic, scalable model for integrating data literacy and data quality reasoning into everyday classroom practice.

3 Materials and Methods

ROSS is a collaborative initiative between the University of Missouri's (MU) Limnology Lab and the STEM Research Center at Oregon State University. The program currently partners with two high schools: Waterville-Elysian-Morristown (WEM) High School in Waterville, Minnesota, and Rock Bridge High School (RBHS) in Columbia, Missouri, with students participating between the 2017 and 2024 academic years. The program combines classroom instruction with field and laboratory activities, allowing students to collect, analyze, and interpret water quality data from their local water bodies. Students are trained to collect shoreline surface water samples and record detailed field notes. During class time, students participate in a range of ROSS activities, including lectures, hands-on sampling, laboratory procedures, and data analysis.

3.1 Schools and Lakes

WEM High School is located in rural southern Minnesota, along the shore of Lake Sakatah (Figure 1). This proximity to the lake provides a unique opportunity for students to engage in place-based environmental science through the ROSS program. Lake Sakatah is a shallow (maximum depth of 3.8 m), dimictic eutrophic lake that experiences seasonal cyanobacterial blooms, making it an ideal site for year-round monitoring. Students at WEM have a strong cultural and emotional connection to the lake, which is even referenced in their school song. This sense of place enhances student engagement and ownership of the scientific process. Under the guidance of science teacher Mike Richards, participating students were enrolled in 11th and 12th grade science classes, which met in 45-minute sessions. An average of 61 students participated each year (2019: 60; 2020: 60; 2021: 60; 2022: 60; 2023: 60; 2024: 66).

RBHS, located in urban Columbia, Missouri, offers a contrasting context for the ROSS program (Figure 1). The school sits adjacent to Bethel Lake, a small, shallow (maximum depth of 4.2 m), warm monomictic, eutrophic urban reservoir. Bethel Lake provides a rich site for studying nutrient dynamics and cyanobacterial bloom formation in urban watersheds. Led by environmental science teacher Greg Kirchhofer, RBHS students were enrolled in 11th and 12th grade environmental science classes, which met for 90 minutes. An average of 21 students participated annually (2017: 20; 2018: 20; 2019: 20; 2020: 18; 2021: 22; 2022: 20; 2023: 20; 2024: 28).

3.2 Water Sampling Process

Students collect weekly water samples from shoreline sites near their respective water bodies, Sakatah and Bethel Lakes, during the academic years of the ROSS program implementation. Samples were then processed, frozen, and transported in lightproof coolers maintained at 4°C to the MU Limnology Lab, where they remained frozen until analysis. To assess the reproducibility of student-collected samples, MU Limnology Lab personnel collected parallel "side-by-side" samples three to four times per year during school visits, at the same locations and times as student sampling.

In the field, students received hands-on training in proper water sample collection techniques. They learned to collect water using a 2 L HDPE bottle with a handle and sampling rod, and were instructed to gently clear away any surface scum to avoid contaminating the sample. Additionally, students were trained to thoroughly rinse the 4 L HDPE bottle with lake water before filling it from the 2 L bottle, and to take water from a depth of approximately 0.5 m to represent the surface water layer.

Apart from techniques for sample collection, students were taught how to complete the first section of the field sheet (Figure 2), which included recording the name of the person collecting the sample, the date, air temperature, weather conditions (e.g., sunny, rainy), wave conditions (e.g., rippled, rough), and ice cover status (ice-covered or ice-free). They were also instructed to use the "Comments" section to document any relevant environmental or site-specific observations, such as recent extreme rainfall, flooding events, or unusual lake conditions that might influence water quality.

In the classroom laboratory, students were trained to process water samples as outlined in Figure 2 and to distribute them into the appropriate containers for further analyses. During this process, they learned how to prevent contamination (e.g., properly handling filters and toxin vials), label samples accurately (e.g., recording the date and volume of water filtered), and store them properly for transport. Students were also taught to record all label information on the field sheet, including filter numbers, volumes of water filtered, and other relevant details, to ensure accurate documentation for future analyses at the MU Limnology Lab.

3.3 Laboratory Analysis in the MU Limnology Lab

Samples were analyzed for total nitrogen (TN), total phosphorus (TP), chlorophyll a (CHL-a), total suspended solids (TSS), and the cyanotoxins microcystin (MC) and cylindrospermopsin (CYL). TN concentrations were measured in triplicate using second derivative spectroscopy (Standard Methods 4500-N C; Crumpton et al., 1992). TP concentrations were analyzed in triplicate by first digesting samples with ammonium peroxydisulfate (Standard Methods 4500-P B), followed by measurement using the ascorbic acid colorimetric method (Standard Methods 4500-P E; APHA, 2017). TSS was assessed using the standard tare-weight method (Standard Methods 2540-D E) wherein triplicate aliquots were filtered through 1.5 μm Whatman glass fiber filters (934-AH), dried at 105°C for 20–30 minutes, and subsequently combusted at 550°C for 20 minutes (APHA, 2017).

CHL-a concentrations were measured from samples filtered onto 0.7 μm GFFs, and pigments were extracted using ethanol (Knowlton, 1984; Sartory and Grobbelaar, 1984). Fluorescence readings were obtained using a Turner Designs TD-700 fluorometer for samples collected in 2019, a Cary Eclipse Fluorescence Spectrophotometer in 2020, and a Turner Designs Trilogy fluorometer from 2021 through 2024 (North et al., 2025a,b). MC and CYL were measured using Abraxis enzyme-linked immunosorbent assay (ELISA) kits. Prior to analysis, samples were freeze-thawed three times to lyse cyanobacterial cells and release intracellular toxins, then filtered through 0.45 µm GFFs to remove cellular debris. Further details on analytical detection limits and instrumentation are provided in North et al. (2025a,b).

3.4 Student Training and Data Assessment Activities

Across eight years of implementation, we have iteratively refined the program's structure and strategies for engaging students. We adopted an approach based on inquiry-based science education and the use of embedded assessments to not only assess student learning outcomes, but to provide points of reflection for the students (Kosmala et al., 2016). From 2019 to 2022, the ROSS program consisted of two in-person training days held at the beginning of each academic year. During the first session, students received an introductory presentation on water quality monitoring efforts at the MU Limnology Lab, including programs such as the Statewide Lake Assessment Program (SLAP), the Lakes of Missouri Volunteer Program (LMVP), and specifically the goals and structure of the ROSS program. The training introduced students to foundational limnological concepts, including types of inland waters, lake mixing patterns, and thermal stratification. On the second day, students participated in hands-on field and laboratory training focused on sample collection and processing. A flyer outlining the sampling process was distributed to all participants (Figure 2), and a full year's supply of sampling materials was provided to each classroom to enable weekly water sample collection throughout the academic year.

We expanded the 2022–2024 curriculum to include multiple presentation-based sessions, skill-building and reflection activities, and field training events integrated throughout the school year. At the start of each academic year, students received two in-person training days with increased emphasis on data literacy skills, understanding of limnology, and how they are supporting limnology research. The first day featured a dedicated lecture on limnology, covering inland water types, major areas of limnological research, harmful algal blooms (HABs), eutrophication, thermal stratification, mixing regimes in lakes, and water quality monitoring efforts at the MU Limnology Lab. Students also learned about their local water bodies and the ecological services they provide, along with a review of current trophic state. The second day followed a similar format; however, students now complete hands-on sample processing training in the field, allowing them to practice the whole process of water collection, filtration, and field-sheet completion directly at the sampling sites. The school visit concluded with a Limnology Knowledge Check, a short survey containing multiple-choice questions on water science and limnology, students' goals for participating in the program, interests and concerns, and their understanding of how the ROSS program supports the health of lakes and reservoirs.

In November each year, students participated in a follow-up training session focused on Quality Assurance and Quality Control (QAQC) in water quality monitoring. This session helped students understand sources of error in sample collection and processing and introduced QAQC techniques for achieving high-quality data. The session explained key QAQC concepts such as precision vs. accuracy, assurance vs. quality control, and common error types, as well as techniques including blanks, calibration, detection limits, and sample reruns. This session was delivered either online or in person, depending on school schedules.

In January each year, the ROSS program visited schools to reinforce the importance of winter water monitoring and accurate data collection. A presentation summarized key findings from the paper "Blooms Also Like It Cold," which explores cold cyanobacterial blooms and the importance of winter monitoring (Reinl et al., 2023). Students also engaged in the Data Quality and Analysis Activity using water quality data collected by the previous year's students, practicing Excel equations, regression analysis, and quality control metrics. This activity included guiding questions to assess students' interpretation skills and promote critical thinking about data quality. The WEM students had the opportunity to observe MU Limnology Lab staff collect samples and record temperature, dissolved oxygen, and other parameters using an EXO3 multiparameter probe (YSI, Yellow Springs, OH, USA) under ice-covered conditions. Because Bethel Lake is a warm monomictic lake and remains ice-free during winter, RBHS students did not participate in a winter field visit.

The last training session each school year was scheduled in April. This visit was designed to present and interpret the water quality data collected by students over their academic year, allowing students to review their results and connect them to earlier lessons on QAQC and data interpretation. The MU Limnology Lab produced educational videos covering water quality monitoring efforts of SLAP, LMVP, and ROSS, as well as laboratory analysis procedures, shared with teachers and students to bridge classroom learning with real-world scientific applications. During the last school visit, students completed a post-survey including the Knowledge Check—with the same five limnology-focused questions as the first Knowledge Check and two additional questions related to interpreting a graph of seasonal water temperature, along with reflective questions designed to evaluate the overall impact of the ROSS program on their learning outcomes, science identity, and experience.

3.5 Statistical Analysis

To assess the reproducibility of student-collected samples, we compared water quality parameters between samples collected by students and those collected by MU Limnology Lab personnel during concurrent site visits. Mann–Whitney U tests were used due to the non-parametric distribution of water quality parameters in this study. A significance level of $\alpha = 0.05$ was used for all statistical comparisons. All statistical analyses were conducted in R (version 4.3.2).

We evaluated students' performance in sample processing over time by comparing the frequency of field sheet errors between two training periods: the "General Training" (2019–2022) and the "Extended Training" (2022–2024). Because field sheet entries at RBHS were completed by the teacher, we focused our analysis on field sheets from WEM High School, which were filled out independently by students. Fisher's exact test was used to assess whether error rates differed significantly between the two training periods. Descriptive statistics were also used to identify the most frequent types of errors recorded in each period.

Coefficients of variation (CV) and data range were calculated for total suspended solids and chlorophyll-a triplicates for each sampling event. Established QC criteria from the MU Limnology Lab were applied: a CV < 25% or a range < 0.2 mg L^{-1} for TSS, and a CV < 25% or a range < 1.0 µg L^{-1} for CHL were considered acceptable. Samples exceeding these thresholds were flagged as needing additional quality control. Chi-square tests of independence were performed to assess whether the proportion of samples meeting QC standards differed between training periods.

To assess students' understanding of data quality, we analyzed their responses to the Knowledge Check questions from the beginning and end of the school year, and examined their responses to questions from the data quality activities. We performed descriptive statistics on the Knowledge

Check results and ran Wilcoxon signed-rank tests to compare responses between the beginning and end of the school year. Open-ended responses were analyzed using a thematic content analysis approach. We conducted initial coding to support consistency and enhance analytical rigor, then used an AI-based language model (Microsoft Copilot, powered by OpenAI's GPT-4) to assist with identifying emergent themes and refining code categories, which we reviewed and validated to ensure alignment with the study's objectives and context. This project was reviewed by the University of Missouri Institutional Review Board and determined to be exempt from further review.

4 Results and Discussion

4.1 Data Quality

We examined 74 field sheets for the general training and 90 field sheets for the extended training periods collected from WEM High School. Evaluating the impact of training on student performance showed a significant improvement in the proportion of mistake-free field sheets from 57 to 87% following implementation of extended training. This improvement was also accompanied by a substantial reduction in high-error field sheets (defined as those containing more than three mistakes). During the general training, 24% of field sheets contained more than three mistakes, whereas no field sheets exceeded this threshold in the extended training period (Figure 3A; Fisher's exact test, $p = 2.01 \times 10^{-7}$).

The type of mistakes also shifted across training periods. During the general training periods, the most common mistakes occurred with the TSS filter (24% of field sheets, $p = 1.487 \times 10^{-5}$) and CHL-a filter (22% of field sheets, $p = 1.094 \times 10^{-6}$) entries, often involving missing filter numbers or volume of water filtered. In the extended training period, the entries most commonly missing were water temperature (10% of field sheets, $p = 1$) and wave condition (6% of field sheets, $p = 0.063$).

These statistically significant improvements suggest that structured training and repeated reflective engagement with sampling protocols enhance students' procedural rigor. This finding aligns with prior research demonstrating that citizen scientists, including youth, can generate high-quality data when supported with appropriate training and scaffolding (Albus et al., 2019; Lewandowski and Specht, 2015). Kobori et al. (2016) and Vohland et al. (2021) further emphasize that training strengthens both data quality and participant engagement, outcomes mirrored in the ROSS program's extended curriculum. One caveat to this before-and-after comparison is that teachers' growing experience with the protocols over time may also have contributed to improved outcomes.

We further evaluated the quality of 67 TSS and 90 CHL filter-triplicate sets prepared during the two training periods (Figure 4). For TSS, the proportion of triplicates meeting the MU Limnology Lab QC standard did not differ significantly between training periods ($\chi^2 = 0.370$, $p = 0.543$). In contrast, CHL triplicate quality improved substantially under the extended training period, with a significantly higher proportion meeting QC standards compared to the general training period ($\chi^2 = 17.915$, $p = 3.1 \times 10^{-5}$).

High school students successfully reproduced water processing following the standard protocol used by MU Limnology Lab personnel, as no significant difference was detected in water quality parameters between student and lab personnel samples (Figure 5). These findings provide strong evidence that, when equipped with enhanced training and structured support, students can generate data that meet professional scientific standards, reinforcing the growing body of literature demonstrating that participatory science programs can produce scientifically valid datasets within rigorous quality assurance frameworks (Lewandowski and Specht, 2015; Albus et al., 2019).

4.2 Student Understanding of Data Quality

To assess students' understanding of data quality, students filled out a Limnology Knowledge Check at the beginning and end of the school year, measuring (1) their understanding of limnology and cyanoHABs, (2) their understanding of data quality issues, and (3) their understanding of how to mitigate those issues. Knowledge Check results showed measurable improvement in students' basic understanding of limnology and cyanoHABs (Figure 6).

There was a significant increase ($p = 0.00009$) in students' knowledge of limnology from the beginning to the end of the school year. The question with the largest difference in correct responses was "What is Chlorophyll a?", which exhibited a 24.4% increase in correct responses. Two additional questions in the post-Knowledge Check asked students to respond to a simple graph showing the relationship between water temperature and month. The graph was interpreted correctly by 79% ($n = 90$) of students, and 81% ($n = 90$) correctly inferred what the graph would depict if it included an additional 6 months of data. The Knowledge Checks demonstrate that students understand the basic goals and processes of the program, including limnology concepts, with some students showing deeper ecological awareness.

To further assess understanding of the ROSS program and cyanoHABs, we analyzed an additional question in the Last Check survey asking students to describe the sampling process as if introducing a new student to the program ($n = 46$). Many students demonstrated awareness of water quality indicators, with 61% ($n = 28/46$) referencing concepts such as cleanliness, presence of toxins, and safety. Over half (50%, $n = 23/46$) explicitly referenced lakes, wildlife, plants, or environmental conditions, reflecting a general grasp of lake health and basic limnological concepts. Procedural knowledge was less consistently articulated but still evident: 13% of students ($n = 6/46$) described specific components of the sampling process, such as collecting water, using bottles or containers, filtering samples, or following step-by-step procedures. These responses indicate that students gained both conceptual and procedural awareness of water quality monitoring through participation in the ROSS program, with variability in depth of understanding across individuals.

> *"You're collecting samples to understand the harmful effects algae blooms have on our lakes. You must clear out the sample of water, make sure to clean it out, and put it in a jug."*

> *"We take samples to see how clean or how toxic the water is. Clean out the container, get water in it, put it in the little test tubes."*

> *"We are monitoring the water quality throughout the year. You collect the water using a bucket attached to the rod. You first rinse it out and then collect. Then you pour the water into a bottle and pump the water through a filter. You do this three times."*

These results are consistent with research demonstrating that participation in authentic, place-based science can support gains in environmental knowledge and basic data interpretation skills (Ballard et al., 2017). Within the School-Based Participatory Science (SBPS) framework, such gains represent important learning outcomes that connect local relevance with scientific content knowledge, even when students demonstrate varying levels of conceptual integration (Smith et al., 2025).

4.2.1 Understanding of Possible Errors in Data Quality

As part of the data quality activity, students were prompted to reflect on the reliability of their water sampling through three guiding questions. In response to "Thinking about the samples your class has collected this year, what kind of errors do you think may occur in the data?," students demonstrated a growing awareness of factors that can compromise data quality. Many students (75%, n = 111/148) attributed lower data quality to contamination. Responses frequently cited contamination from touching filters, using dirty equipment, introducing sediment, and transferring oils from hands or scum into samples. As one student noted: "If your equipment or hands are not cleaned properly, it can interfere with results," while another emphasized that "the tools we use, and how we use them, often change the samples." Procedural errors were mentioned in 61% (n = 148) of responses, including mistakes in following sampling protocols, incorrect dipping techniques, skipping steps, or applying inconsistent methods. Additionally, 43% (n = 148) of students identified environmental factors such as weather conditions, temperature fluctuations, wind, seasonal changes, and sampling location as potential contributors to data variability.

Student recognition of contamination, procedural inconsistency, and environmental variability reflects key components of data literacy as defined by Gummer and Mandinach (2015). These findings support prior work showing that engagement with real, imperfect datasets can help learners move beyond viewing data as error-free and instead recognize uncertainty as inherent to scientific practice (Mandinach and Gummer, 2016).

4.2.2 Mitigation of Errors

Students not only identified sources of error but also proposed thoughtful strategies to mitigate them. In response to questions about improving data quality, 50% (n = 148) of students offered concrete suggestions, demonstrating a growing sense of ownership over their scientific practices. Many emphasized being more careful and deliberate during sampling: suggestions included slowing down to increase precision, using gloves to prevent contamination, and avoiding contact with the bottom of the sampling site or the filters. One student advised, "Go a little bit slower so we can be more precise and accurate when taking samples," while another noted, "Be more careful about not touching the bottom, and be sure to not touch the filters with your hands." Students also recognized the value of consistency in sampling methods: several responses highlighted the need to follow instructions closely and standardize sampling locations. One student recommended, "Make sure we are running the same amount of water through the filters," pointing to the importance of uniform procedures in producing reliable data. By encouraging students to think critically about contamination, procedural rigor, and environmental influences, the program helped build a foundation for responsible and reflective scientific practice.

The ability to propose improvements to data collection indicates early reflective and metacognitive reasoning, a hallmark of inquiry-based science learning (Hamilton et al., 2009). Through iterative sampling and structured reflection, students began to connect their individual actions to broader data quality outcomes, reinforcing findings that participatory science programs can simultaneously support scientific rigor and student learning when reflection is intentionally integrated (Ballard et al., 2017; Smith et al., 2025).

The integration of a mid-year data quality assessment and multiple reflection points closely aligns with the SBPS framework, which emphasizes authenticity, relevance, collaboration, and learning outcomes (Smith et al., 2025). Student reflections revealed increasing awareness of contamination, procedural rigor, and environmental variability, core elements of data literacy (Gummer and

Mandinach, 2015). Consistent with prior literature, the inquiry-based design of the ROSS program and engagement with “messy” data supported students’ development of analytical reasoning and understanding of scientific uncertainty (Mandinach and Gummer, 2016; Hamilton et al., 2009). By engaging students in real-world environmental monitoring and iterative reflection, the ROSS program fostered scientific literacy, environmental agency, and data reasoning skills (Ballard et al., 2017).

5 Conclusion

This study demonstrates that the ROSS program simultaneously supports high-quality environmental monitoring and meaningful student learning, illustrating how school-based participatory science can advance both scientific and educational goals. By pairing a rigorous data quality comparison with assessments of student learning and reflection, this work highlights how program design influences both the reliability of student-collected data and the educational experiences that produce it.

Comparisons between water quality measurements collected by high school students and MU Limnology Lab personnel revealed no statistically significant differences across parameters, indicating that student sampling can generate scientifically valid data. At the same time, consistent patterns in the data provide targeted insight for refining training practices. Specifically, lower average TSS values and higher chlorophyll-a concentrations in student samples highlight the importance of experience-dependent sampling behaviors, such as filtering to an endpoint rather than a fixed volume and consistently avoiding surface scums during collection. Field conditions further influenced protocol fidelity; for example, sampling from elevated platforms limited students’ ability to perform surface-sweeping techniques effectively compared to sites with accessible shorelines. These findings underscore how environmental context and procedural experience interact to shape data quality in participatory monitoring programs.

Beyond scientific outcomes, the ROSS program produced meaningful educational benefits for participating students. Results from the Limnology Knowledge Checks, reflective survey responses, and data quality activities demonstrate statistically significant gains in students’ limnology knowledge, emerging data literacy skills, and improved ability to interpret ecological data visualizations. Through repeated engagement with authentic sampling and analysis tasks, students developed a clearer understanding of why data quality matters and how methodological decisions influence scientific conclusions. These outcomes are particularly valuable in place-based contexts, where students can directly connect classroom concepts to environmental issues affecting their local communities.

Several limitations should be considered when interpreting student learning outcomes. Participation levels varied across schools and years, and incomplete pre–post survey matching limited paired statistical analyses. Additionally, the Knowledge Check assessed foundational understanding rather than deeper reasoning or long-term retention, and qualitative responses varied widely in depth and clarity. Because ROSS is embedded within existing science courses, learning gains cannot be attributed solely to program participation, and differences in instructional context may have influenced outcomes. Longer-term impacts on science identity, self-efficacy, and STEM persistence remain important areas for future investigation.

Building on these findings, future iterations of the ROSS program will place increased emphasis on strengthening and standardizing training related to data quality and scientific practice. Planned refinements include expanded hands-on practice with filtration endpoints, enhanced field-based demonstrations of critical sampling steps, increased opportunities for peer mentoring, and more structured reflection activities that explicitly link sampling decisions to data outcomes. Where feasible, adoption of electric filtration pumps could reduce physical constraints and improve consistency in TSS collection. These adjustments aim to better align training intensity with both scientific rigor and student learning needs.

Future research should further explore the reciprocal relationship between student learning and data quality in school-based participatory science. Longitudinal analyses across additional sites and cohorts, integration of standardized quality assurance metrics, and mixed-methods approaches linking individual learning trajectories with data outcomes would deepen understanding of how participatory programs can be optimized. Ultimately, the ROSS program demonstrates that with intentional design, structured training, and reflective practice, high school students can serve as capable contributors to long-term environmental monitoring while developing the knowledge, skills, and scientific habits essential for engagement in environmental science.

6 Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

7 Author Contributions

ZMK: Conceptualization, methodology, investigation, data curation, formal analysis, visualization, writing–original draft, writing–review and editing. HAF: Conceptualization, methodology, formal analysis, supervision, writing–original draft, writing–review and editing. LH: Formal analysis and visualization. RLN: Conceptualization, methodology, resources, funding acquisition, project administration, supervision, data curation, writing–review and editing. All authors approved the final manuscript.

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10 Data Availability Statement

Student survey data collected for this study are not publicly available in order to protect student privacy. De-identified survey data may be made available from the corresponding author upon reasonable request. ROSS water quality datasets are publicly accessible through the Environmental Data Initiative (EDI) at: https://doi.org/10.6073/pasta/a736f7c0c9bab0092a9f9e9e77fd6722 [edi.1830.2] and https://doi.org/10.6073/pasta/04c5314549c30b280b8dafb9008f8db4 [edi.1829.2].

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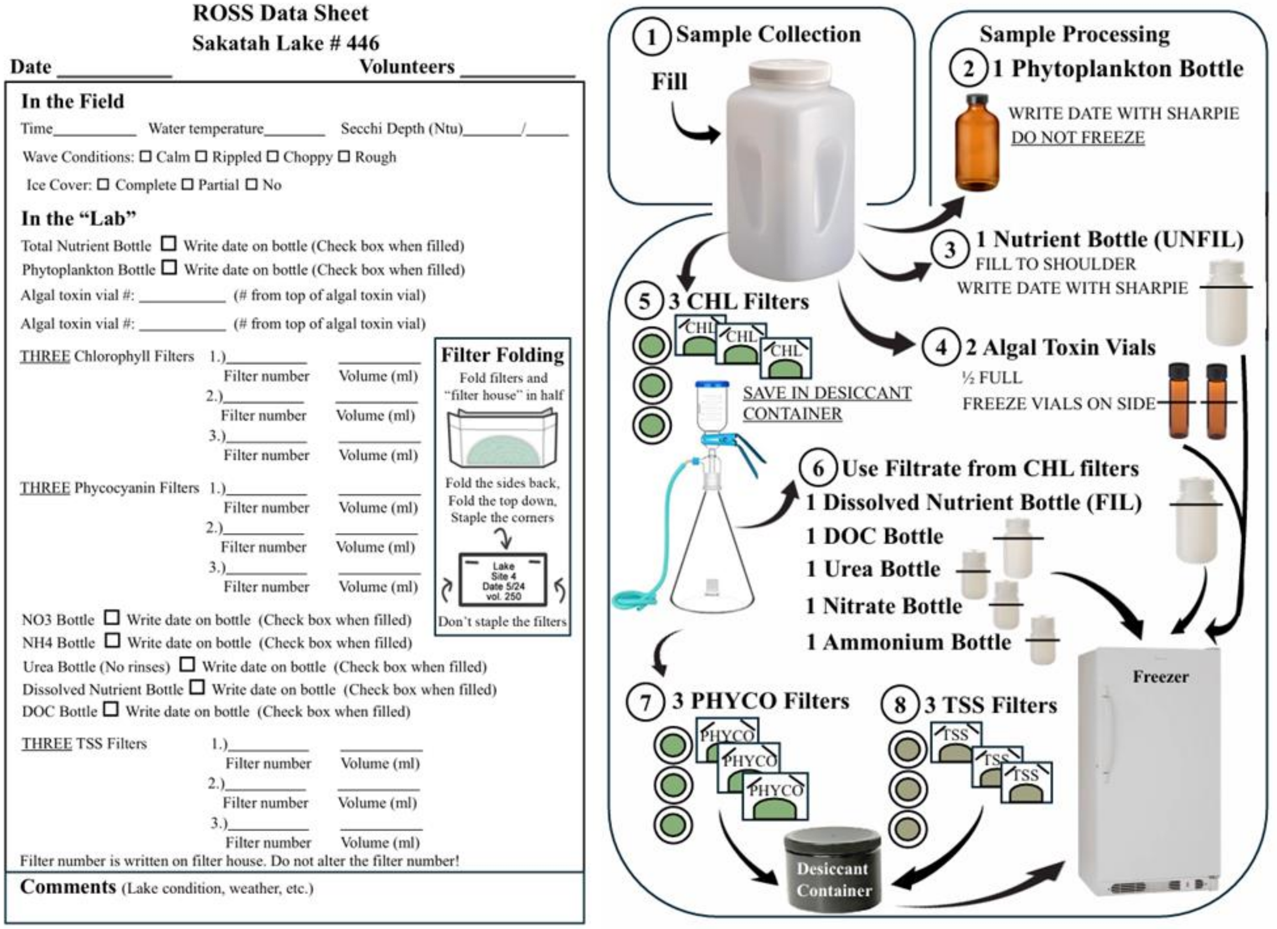
Figure 1. Geographic locations of water bodies (Sakatah Lake and Bethel Lake) and high schools (Waterville-Elysian-Morristown and Rock Bridge) studied in the ROSS program.



ROSS Data Sheet

Sakatah Lake # 446

Date ____________ **Volunteers** ____________

In the Field

Time__________ Water temperature_______ Secchi Depth (Ntu)______/_____

Wave Conditions: ☐ Calm ☐ Rippled ☐ Choppy ☐ Rough

Ice Cover: ☐ Complete ☐ Partial ☐ No

In the "Lab"

Total Nutrient Bottle ☐ Write date on bottle (Check box when filled)

Phytoplankton Bottle ☐ Write date on bottle (Check box when filled)

Algal toxin vial #: __________ (# from top of algal toxin vial)

Algal toxin vial #: __________ (# from top of algal toxin vial)

THREE Chlorophyll Filters
1.)__________ __________
Filter number Volume (ml)
2.)__________ __________
Filter number Volume (ml)
3.)__________ __________
Filter number Volume (ml)

THREE Phycocyanin Filters
1.)__________ __________
Filter number Volume (ml)
2.)__________ __________
Filter number Volume (ml)
3.)__________ __________
Filter number Volume (ml)

Filter Folding
Fold filters and "filter house" in half
Fold the sides back, Fold the top down, Staple the corners
Lake
Site 4
Date 5/24
vol. 250
Don't staple the filters

NO3 Bottle ☐ Write date on bottle (Check box when filled)

NH4 Bottle ☐ Write date on bottle (Check box when filled)

Urea Bottle (No rinses) ☐ Write date on bottle (Check box when filled)

Dissolved Nutrient Bottle ☐ Write date on bottle (Check box when filled)

DOC Bottle ☐ Write date on bottle (Check box when filled)

THREE TSS Filters
1.)__________ __________
Filter number Volume (ml)
2.)__________ __________
Filter number Volume (ml)
3.)__________ __________
Filter number Volume (ml)

Filter number is written on filter house. Do not alter the filter number!

Comments (Lake condition, weather, etc.)

Figure 2. Field sheet and sampling process diagram designed for the ROSS program. This updated version was adopted in the 2024 academic year.

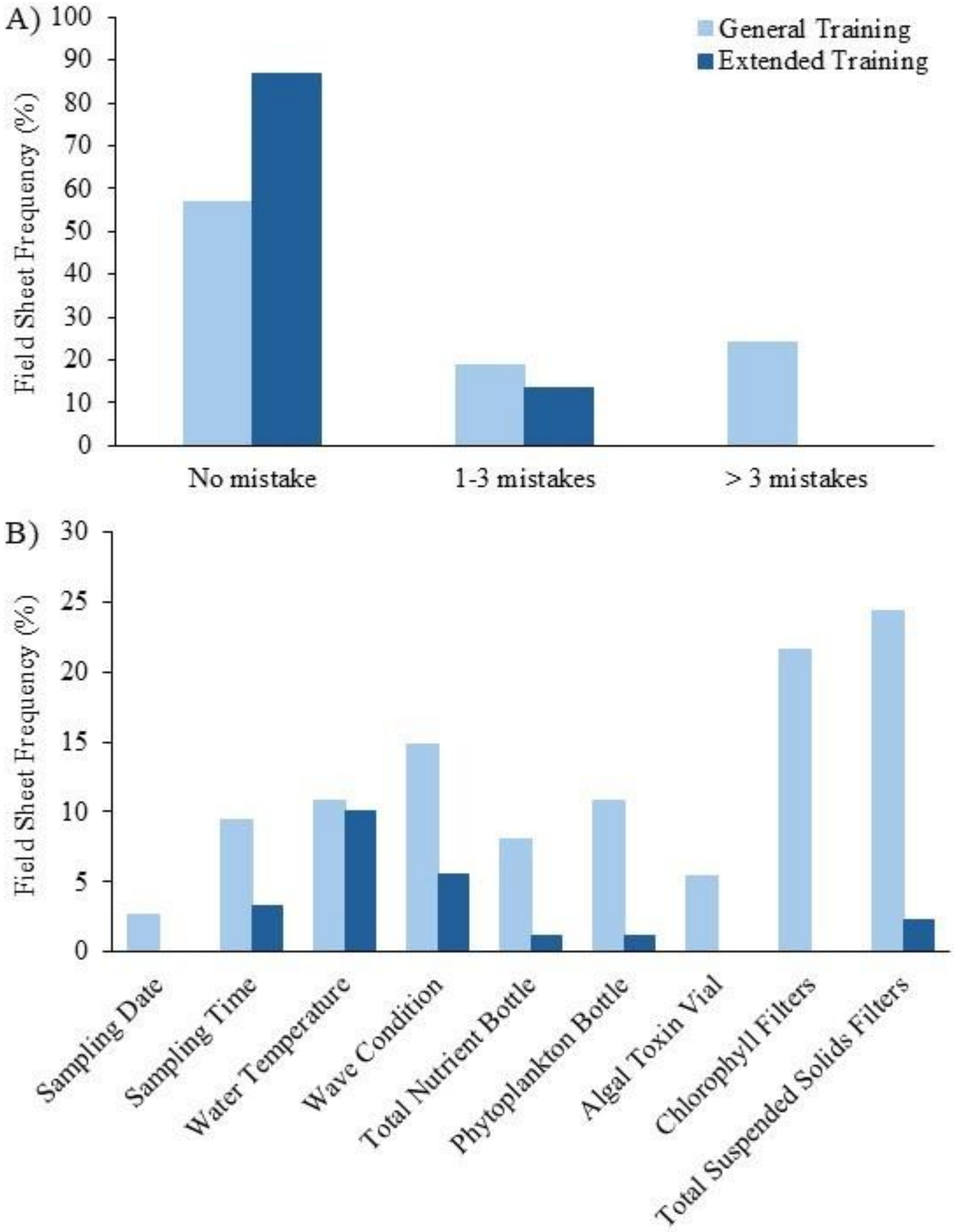


Figure 3. (A) Distribution of field sheets containing no mistakes, 1–3 mistakes, or >3 mistakes, and (B) distribution of mistake type during the general (n = 74 field sheets) and extended training (n = 90 field sheets) periods in the ROSS program implemented at Waterville-Elysian-Morristown High School. Bars show the frequency of field sheets in each category.

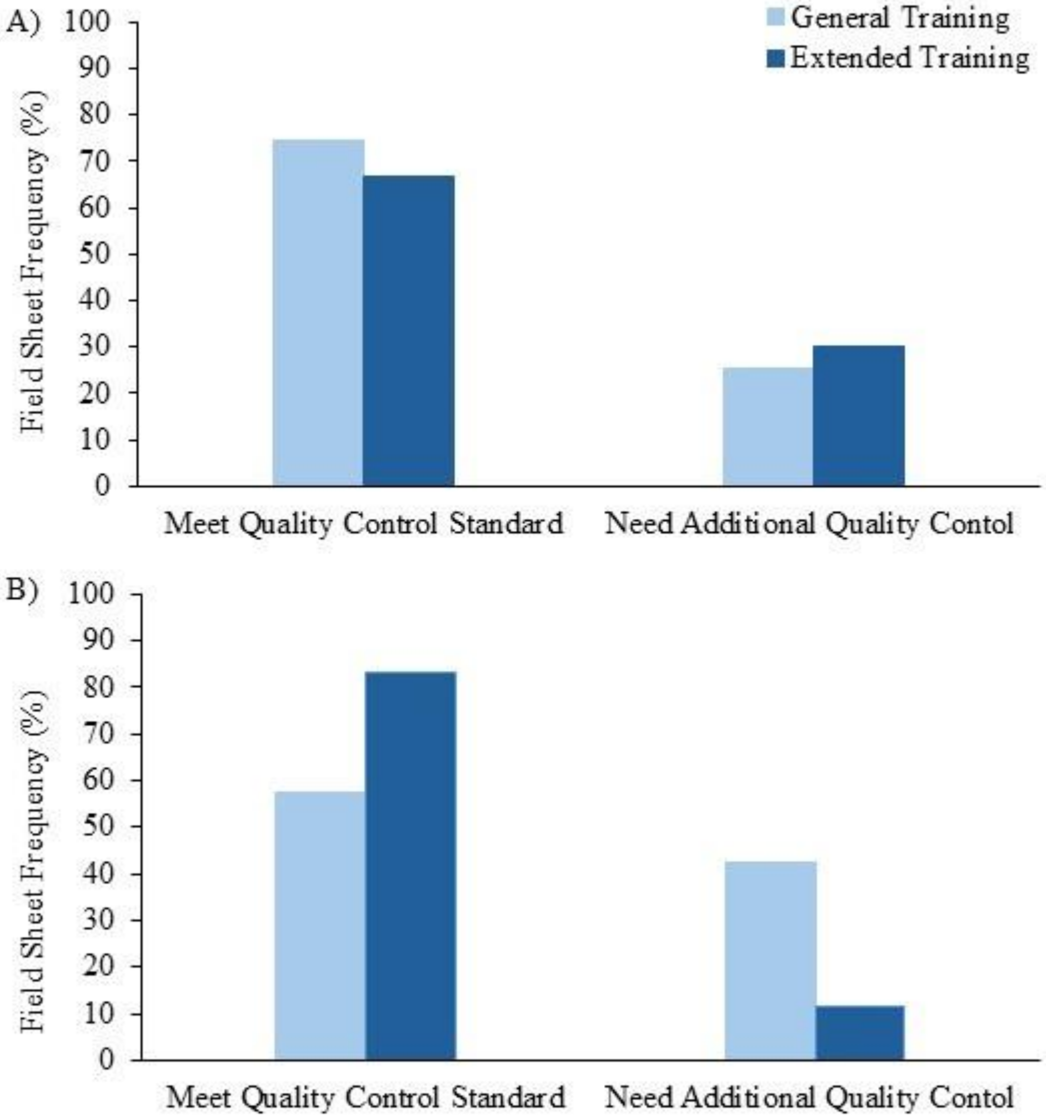


Figure 4. Quality control of (A) total suspended solids and (B) chlorophyll-a filters prepared by high school students during the general and extended training periods in the ROSS program at Waterville-Elysian-Morristown High School. Bars show the frequency of filter triplicates in each category.

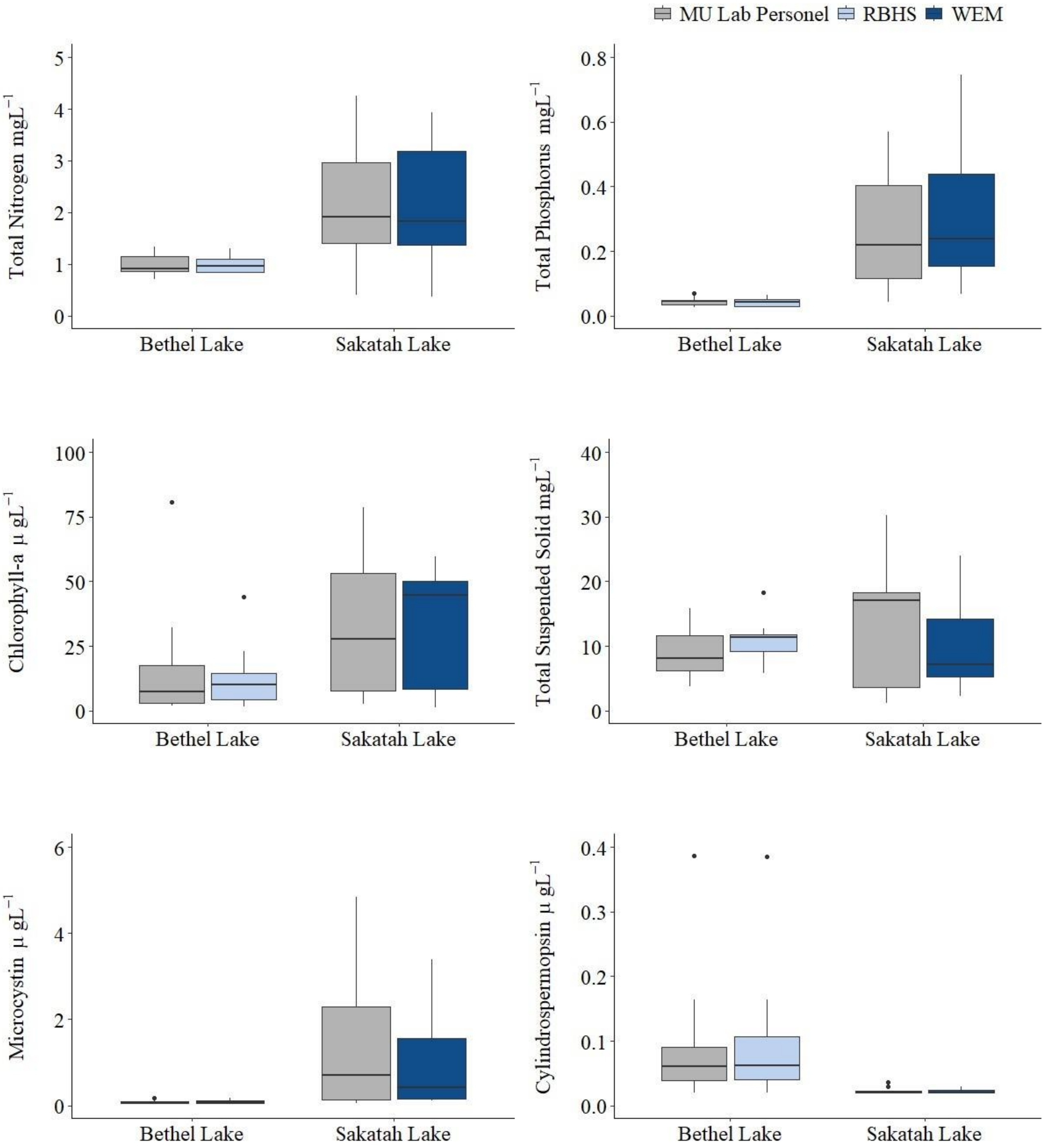


Figure 5. Water quality parameters collected by WEM and RBHS students, and side-by-side samples collected by MU Limnology Lab personnel from Bethel Lake and Sakatah Lake throughout the ROSS program.

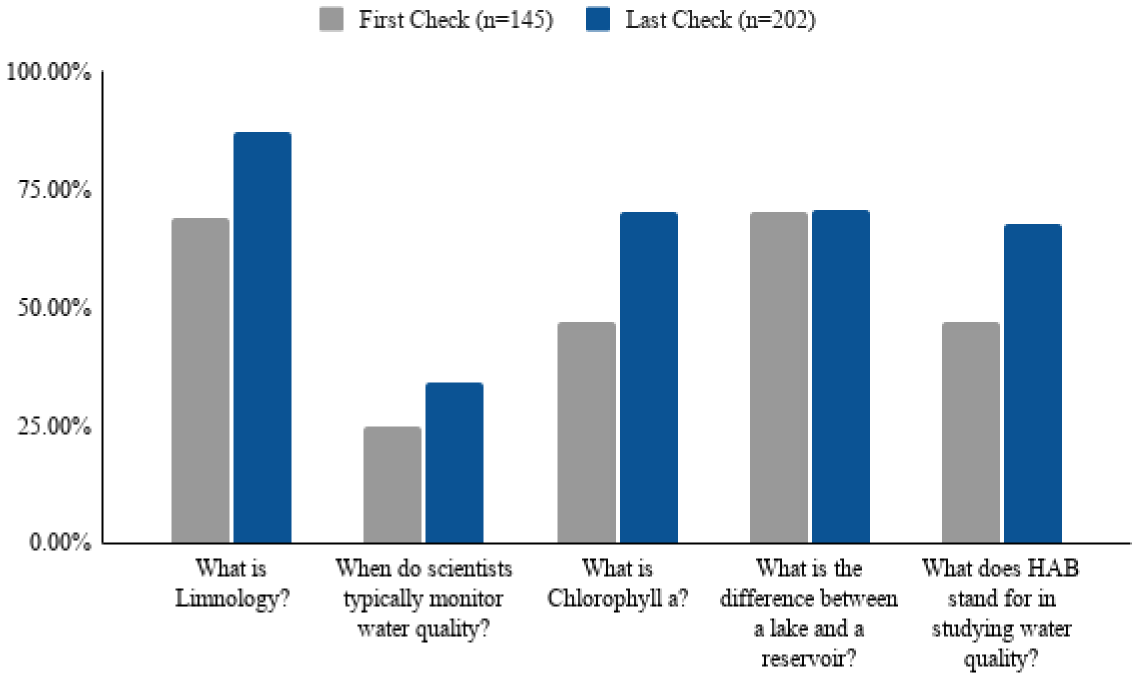


Figure 6. Limnology Knowledge Check questions answered by WEM and RBHS students. The first check was conducted at the beginning of the school year (September), and the last check was conducted at the end (April).