THE UNIVERSITY OF NORTH CAROLINA

FALLS LAKE STUDY

Final Report to the North Carolina General Assembly, December 2023

collaboratory
science. policy. solutions.

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

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NC Collaboratory website: collaboratory.unc.edu

Falls Lake Study report: nutrients.web.unc.edu

Foreword

Legislative Charge

During the 2016 legislative short session the North Carolina General Assembly approved a special provision in the annual budget bill, "Development of New Comprehensive Nutrient Management Regulatory Framework." This section directed UNC-Chapel Hill to oversee a study and analysis of nutrient management strategies and synthesis of existing water quality data in the context of Jordan and Falls Lake (See Appendix I for full legislative text).

The newly formed North Carolina Collaboratory was designated by UNC-Chapel Hill leadership to manage the study. The Collaboratory staff worked with faculty and issue experts across the UNC system to develop the research team and identify the critical research questions that needed to be addressed. Mike Piehler, Director of the UNC Institute for the Environment, served as the faculty lead and coordinated the research team throughout the course of the study.

The legislation provided $500,000 annually over six years beginning in FY 2016 to 2017 with progress reports on the study required every year. The first three years of the study were focused on Jordan Lake, culminating in a final legislative report that was submitted in December 2019. The Jordan Lake report and supporting documents can be found at http://nutrients.web.unc.edu.

In the summer of 2019, the research team transitioned to focusing on Falls Lake. The original legislation establishing the study mandated a final report for Falls Lake in 2021. The 2018 budget bill extended this deadline, requiring study results to be completed by the end of 2023, with interim updates in advance of the final report.

In the 2021 budget bill, Session Law 2021-180 (Section 8.5), the legislature appropriated an additional $750,000 for the Falls/Jordan Lake study. The bill provided that any remaining funds at the end of the 2021-22 fiscal year shall not revert but remain available to support the study until December 31, 2023.

That additional investment allowed for the continuation of research topics and additional data gathering to reach fuller and more robust findings. Furthermore, the additional funds provided support for new research areas in the last couple of years of the study.

Importantly, while the submittal of this legislative report and the associated recommendations for the future management of Falls Lake concludes the formal work of the study, continued research and partnerships on many of the topics that are detailed in the report will continue into the foreseeable future. That ongoing work and acknowledgment that conditions are constantly changing in Falls Lake, thereby requiring the need for adaptive management, is one of the hallmark outcomes of this research and legacy of the study.

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Study Overview

Study Team

Over the course of 2019 to 2023 researchers from UNC-Chapel Hill, East Carolina University, and NC State University conducted a number of research projects focused on both the Falls Lake watershed and the lake itself as part of the study. (A full roster of study team members can be found in Appendix II.) In addition, dozens of graduate students and undergraduate students have conducted research for the study.

This collection of research projects synthesizes interdisciplinary analyses of Falls Lake's nutrient content and fluctuation, the factors that affect it, mitigation strategies and their effectiveness, and financial implications of proposed processes. Several distinct research teams evaluated a number of factors related to the water quality of Falls Lake, including flows in and out of the lake, the potential for the development of toxic algae, review of existing modeling efforts, mitigation strategies and financial resources available for those strategies. That research was guided by fundamental research questions that serve as the foundation of the study. As an example of the topics considered as part of the study, some of these research questions are listed below.

Research Questions

- How do the lake's nutrient levels change during various flow conditions? How does the water movement differ between timescales, and how does this affect nutrient levels in the lake?

- How can we better understand sediment fluxes associated with the lake and the rates of sediment input to the fate of particulate materials?

- Are year-round patterns of cyanobacterial abundance in the lake associated with toxin presence?

- Do onsite wastewater treatment systems increase nutrient concentrations in streams draining to the lake? What are the optimal locations for bioreactors along low-order streams?

- Can the ratio of zooplankton to phytoplankton biomass be used as an indicator of food web health that could guide a site-specific criterion for lake phytoplankton biomass.

- What types of revenue sources are authorized to provide funding for water quality improvement of the watershed and lake?

Water sampling at Falls Lake.

Sharing Research Results

One of the hallmarks of the Falls Lake study has been the engagement of the research team with local governments and other interested parties about the latest findings from the ongoing research. This continued interaction between stakeholders and researchers served dual purposes. First, the external stakeholders provided guidance and input to researchers and helped identify research questions of importance to the study. Secondly, the researchers had the opportunity to share their latest findings and what they might mean for management implications.

In 2021 to 2023, the NC Collaboratory, the Upper Neuse River Basin Association (UNRBA), and the UNC Institute for the Environment jointly held the annual Falls Lake Nutrient Management Study Research Symposia. During the three public meetings, Mike Piehler, faculty lead for the study, provided an overview of the research taking place and Forrest Westall, Executive Director of the UNRBA, presented comments on the re-examination of the Falls Lake Nutrient Management Strategy.

Researchers preparing to take cores at Falls Lake.

The meetings highlighted research in three specific topic areas:

- Watershed Processes
- In-Lake Processes
- Financing and Policy Work

Mike Piehler speaking at the 2023 Falls Lake Study symposium.

Executive Summary and Outcomes

Enabling legislation for the study identified critical components to be included in the work: 1) a review of historical water quality data and its connections to management interventions; and 2) a review of the costs and benefits of other states' nutrient strategies in enhancing water quality.

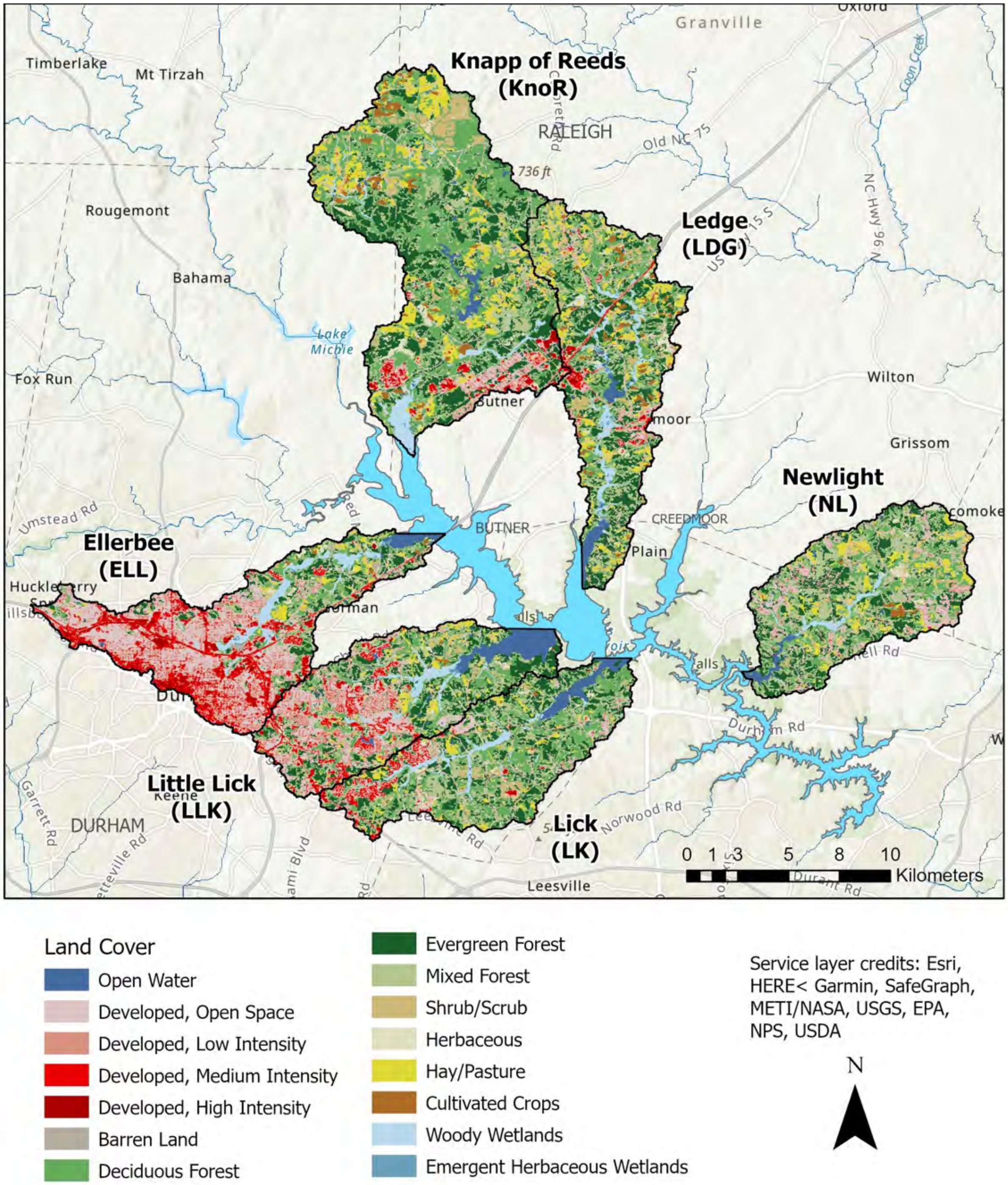
Building on these legislative directives the study team sought to undertake a comprehensive review of a variety of factors that affect water quality in the lake, both from external sources and internal dynamics. Consequently, the study was designed to provide actionable information for policy-makers and key stakeholders to make management decisions throughout the Falls Lake watershed.

The substantial research done for the re-examination of the Falls Lake rules illustrates and highlights the complexity of addressing nutrient overload-enrichments in Piedmont reservoirs. The reductions achieved during Stage I of the rules have removed from the potential inventory of sources most of the load reductions that can be achieved by 2041, the current deadline for accomplishment of the nutrient management strategy. More recent research has established the importance of the significant amounts of "legacy" nutrients stored in the sediments in the reservoirs, in streambanks, and in groundwater, whether from the overuse of fertilizer or onsite septic system loading of groundwaters. The time for natural processes to address the legacy nutrients push the projected date for achievement of the goals of the nutrient management strategy substantially beyond 2041.

Two other important sources of nutrients are atmospheric deposition on impervious surfaces, a source of nitrogen, and sediment in runoff, a source of phosphorous. As the U.S. Environmental Protection Agency (EPA) research shows, stormwater flows are a significant source of nutrient loading that is particularly challenging to resolve in North Carolina. These sources of nutrient loading are outside the ability of the local governments to control.

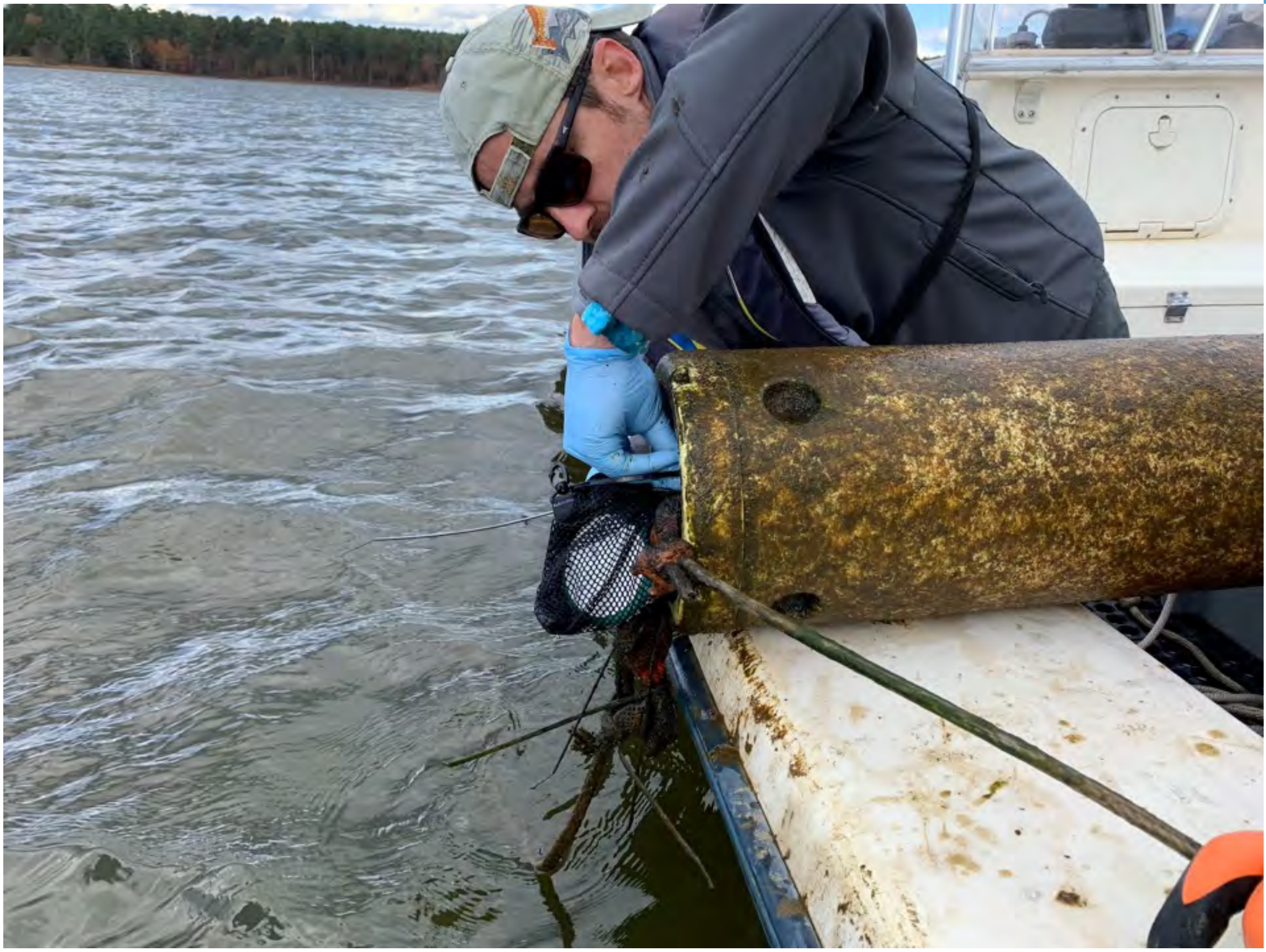
Likewise, loading caused by large storm events such as tropical storms or heavy rainfall is not controlled by the stormwater measures required under the Falls rules. Collectively, these sources of nutrients make it readily apparent that nutrient impairments cannot be resolved by 2041, but instead will take decades to resolve even as new sources of loading are added to the basins.

Falls Lake (Photo courtesy of UNRBA).



Land cover in Falls Lake tributary catchments. Classifications obtained from the 2019 National Land Cover Dataset.

The Falls rules anticipated an extended time for recovery and divided the remedial efforts into two Stages. The research based on more extensive monitoring and modeling confirmed that the remedial efforts will be needed for many years to come, and that few remedial actions can address "legacy" nutrients. The current control efforts have focused on new development, nutrient reductions at the WWTPs using current technology, and agricultural reductions. The existing development loading has had limited reductions, however that source of reductions can be enlarged with the addition of nutrient reduction values for more economically effective technologies and the implementation of the innovative approach to reduction of loading from existing development known as the Interim Adaptive Management Approach. Given the importance of legacy nutrient loading sources and the legislative barriers to local governments achieving reductions from re-developed properties, the needed reductions to achieve an attainment status for the current nutrient WQS will extend long after 2041.



Researchers and DEQ staff at Falls Lake.

It should be noted that the Falls Lake study benefitted tremendously from a couple of factors that enhanced the research over the last four years. First, the many research projects in the Jordan Lake study provided a strong foundation for the research team to build on and refine research questions and methods. Secondly, the multi-faceted work and interest in the research of the UNRBA created a beneficial pathway to share findings and enhance the research questions that were needed through the course of the study. The UNRBA's involvement in the study and the assistance provided by the North Carolina Department of Environmental Quality (DEQ) staff were critical to the research undertaken as part of this study.

The individual research projects that comprise the overall Falls Lake study each shed light on a new discovery or provide information that will assist in further research outcomes. Taken as a whole, the research provides valuable insights into the function of Falls Lake and how the lake is impacted by human activity throughout the watershed.

Outcomes from the study are grouped into two categories:

- Management and Policy Implications
- Scientific Findings of Note

Management and Policy Implications

Financing and Paying for Nutrient Manaement

- The UNC Environmental Finance Center (EFC) concluded that the Interim Alternative Implementation Approach's (IAIA) compliance structure for Falls Lake was successful and significantly decreases the cost of compliance.

- A revenue model where both upstream communities and those communities benefiting from Falls Lake should each be required to fund and support efforts to nutrient management activities in the watershed. In addition to following a polluter pays model, imposing a charge on downstream watershed users could distribute the economic burden more widely based on use.

• One example of this approach could include:
Customers whose drinking water comes from Falls Lake, such as those in the City of Raleigh, could be charged a tax on their water bill that would directly support nutrient management and water quality projects.

• Nutrient management financing approaches used in Jordan Lake are applicable to Falls Lake. These included the creation of a voluntary watershed organization, levying aid from local organizations such as the Soil and Water Conservation Districts (SWCD), levying non-designated utility charges, and creating lake models.

• The EFC recommended using two affordability metrics to consider for the increase of utility rates: the percent of 20th percentile household income and the affordability ratio at the 20th percentile household income. These metrics specifically highlight burdens on low-income customers and are recommended for policymaker use when structuring financing mechanisms to have the lowest impact on low-income customers.

• Additional recommendations from the Jordan Lake study that could be used in Falls Lake include the institution of a property tax, stormwater district tax, sales tax, business improvement district tax, property assessments, a structure like the Maryland Bay Restoration Fee, and introducing a different financing structure for multi-jurisdictional water management organizations.

Supporting Comprehensive Watershed Management

• While local governments have developed a remarkable record of cooperation in their monitoring and modeling efforts in the service of improving water quality in Falls Lake, a new adaptative management strategy is needed. The state should enact statutory changes that allow for and promote a successful nutrient management plan through a cooperative voluntary program led by local governments in the watershed.

• Efforts by the UNRBA to advance the discussion around changes to the site-specific standard should be supported.

• The current existing development rule should be revised to limit the load reductions required of local governments consistent with the statutory limits on the powers and territorial jurisdictions of the local governments.

• Legislation should be adopted to provide for the development of long term plans (20+ years) by local governments to address nutrient reduction needs in reservoirs used for drinking water supplies and that DEQ permits to the local governments would be controlled by the approved long term plans.

Fostering Continued Investment in Land Conservation

• Recognizing that Falls Lake is at the tipping point where approximately 60% of the area is forested, maintaining forested areas, particularly near waterways, is vital to the continued health of the watershed and the affordability of water treatment.

• Presently, the Falls Lake watershed is making great strides to protect land in order to maintain water quality through initiatives such as Upper Neuse Clean Water Initiative (UNCWI) and the IAIA. Any nutrient management strategy in Falls Lake should reflect the successes of these initiatives, including consideration for the function of land conservation within nutrient management strategy.

• The Chesapeake Conservation Atlas serves as a watershed-wide clearinghouse for mapping data, and helps to ensure strategic, long-term coordination between organizations working to conserve lands. Falls Lake requisites a GIS-based mapping and data system that will allow for similar coordination between organizations, such as the UNCWI, and State and local government entities. This system would serve as both a data collection and implementation tool through which significant forested areas can be identified, and land conservation projects can be prioritized throughout the watershed.

Improving Onsite Wastewater Systems in the Watershed

• Due to the cost-prohibitiveness of sewer implementation, from an economic perspective, emphasis should be on repairing malfunctional or compromised Onsite Wastewater Systems (OWS), especially in watersheds with high densities of OWS.

• Collaboration is needed between local county health departments and the NC Department of Health and Human Services to develop a central repository of GIS data for OWS. This information, in addition to community efforts, should be used to identify and repair OWS.

• High-resolution GIS databases characterizing critical OWS information such as location, age, system type, history of malfunctions/repairs, etc. would be a valuable resource to assist efforts to evaluate and manage nutrient transport from OWS to water resources.

• Modeling an OWS inspection program similar to the Todd D. Krafft Septic Health Initiative Program in Nags Head, could help local health departments to identify and spatially reference OWS.

Scientific Findings of Note

Water Circulation and Internal Lake Dynamics

• Attention to circulation of the lake is a crucial factor of water quality outcomes, such as times of slow flow being typically associated with poor water quality.

• The study resulted in an increased understanding of transport in Falls Lake and serves as an important validation of water quality modeling efforts, such as those sponsored by the UNRBA. Temperature and in vivo fluorescence (a measure of chlorophyll-a and related biomass) showed significant spatial variability; however, there were no discernable patterns identified.

Nutrient Loading

• Restoration efforts have been shown to successfully improve bank stabilization and prevent sloughing and further incision of the channel. Bank stabilization efforts focused on protecting the bank toe-region have been shown to reduce erosion by 90%. And simulations indicated that streambank stabilization could provide the greatest potential for the prevention/removal of TP (609 kg P/km/yr) over other restoration practices.

• These restoration activities could also afford other habitat and water quality related benefits. Detailed economic analysis is recommended to compare the cost of repairing these streams or their eroding streambanks against reducing other sources of sediment and associated phosphorus to optimize any investments targeted at reducing negative impacts to the water quality of Falls Lake.

• Annually nitrogen removal by the sediments only accounts for approximately one quarter of the TN inputs from atmospheric deposition, tributary runoff, and fluxes from the sediments. Therefore, policies aimed at reducing anthropogenic nitrogen inputs could mitigate water quality degradation to some extent but will likely not prevent algal blooms completely. Furthermore, excess nitrogen may be a characteristic of urban reservoirs.

• Based on the lack of a strong relationship between zooplankton and phytoplankton biomass for southeastern reservoirs, it is currently unadvisable to pursue setting a site-specific chlorophyll a standard for Falls Lake based on zooplankton: chlorophyll a relationships.

• Atmospheric deposition is a major consideration in determining watershed modeling and should be considered in developing nutrient loading budgets.

• Internal nutrient fluxes from reservoir bottom sediments are another driver of lake quality. Internal loading provides a long-term supply of nutrients that can delay the benefit of external watershed loading reduction.

Example of erosion classifications among Falls Lake reaches.

• Nutrient loading rates from developed lands are typically several times higher than from undeveloped lands.

• N2 fixation suggests that dual management of N and P is warranted for preventing undesirable levels of phytoplankton biomass in Falls Lake.

• Direct measurements of N2 fixation indicate that N2 fixation contributes less than 1% of total N inputs to Falls Lake. Estimated N2 fixation based on the biomass of cyanobacteria capable of N2 fixation is about 6% of tributary inputs. Both methods agree that N2 fixation is a small percentage of total N2 inputs which provides a justification for omitting the process in eutrophication models for Falls Lake.

• Downcore profiles within Falls Lake indicate that the carbon accumulation rate has not changed significantly since the reservoir's construction in the early 1980s. No core shows a significant, progressive increase that would be consistent with a response to rising atmospheric carbon concentrations, nor do they show a significant basin-wide trend.

• Overall, results suggest that strategic floating treatment wetlands placement can provide significant pollutant removal even at low surface coverage rates (i.e., <5%). As previous research in NC suggested 20% FTW coverage was needed to significantly improve water quality treatment, the lowered coverage recommendation may decrease the financial barrier to retrofit wet ponds and incentivize the use of FTWs in watersheds in the state.

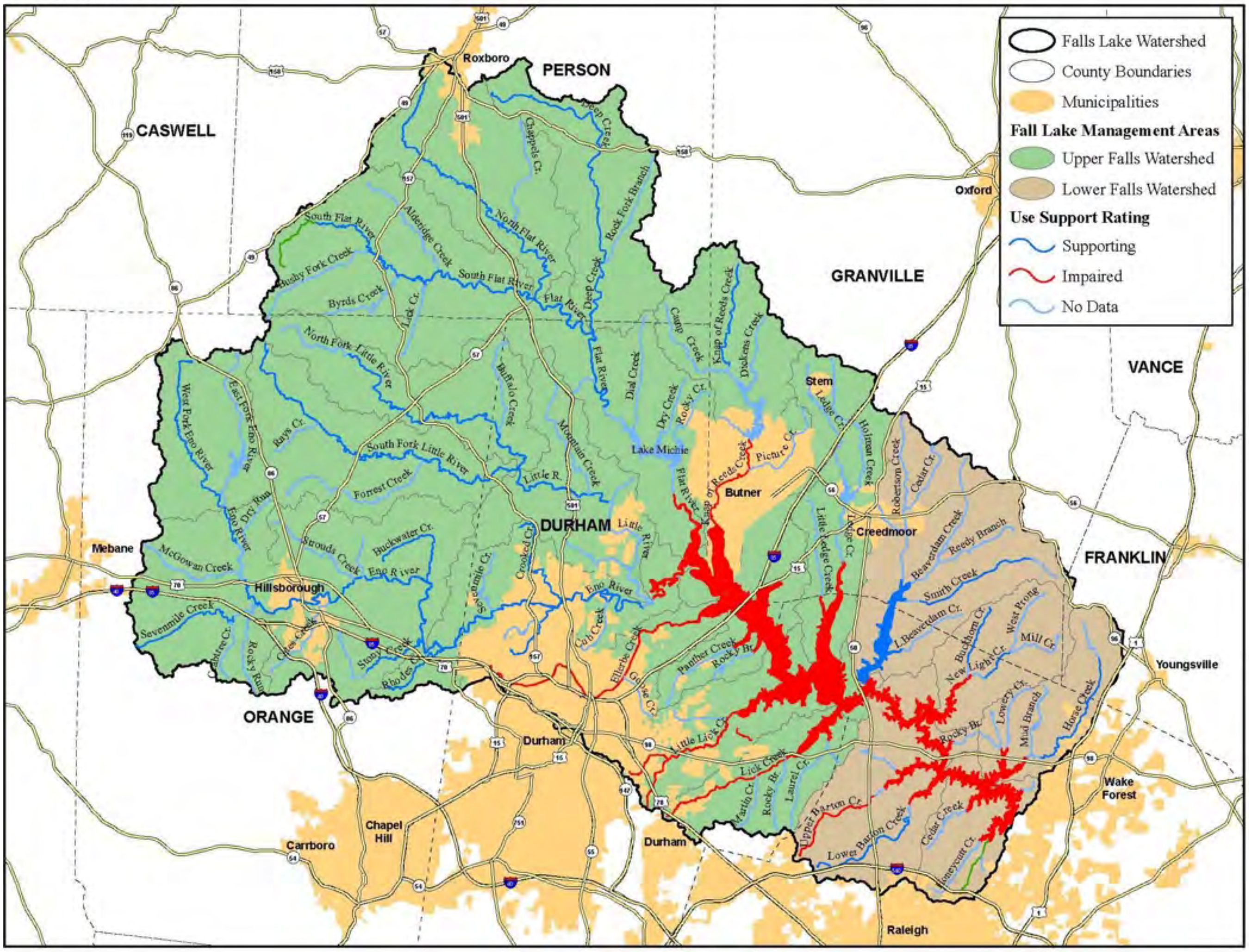
Concerns Related to Toxic Algae

• Continued monitoring of common toxins (of microcystin variants) on a weekly to biweekly basis at selected stations (upper, middle/tributary, lower lake) is highly recommended to resolve toxin dynamics beyond monthly snapshots. Lake research suggests that the eutrophic status of Falls Lake, make it prone to experience intensification of cyanobacterial harmful algal blooms (CyanoHABs) in response to climate change.

• Conduct seasonal surveys (i.e., summer and fall) to determine food web accumulation of cyanotoxins in commonly caught/consumed fish. Toxin accumulation by passive samplers indicate the potential active accumulation of cyanotoxins through the food web.

Water sampling at Falls Lake.

Falls Lake Background



Falls Lake Map. Source: http://portal.ncdenr.org/web/fallslake

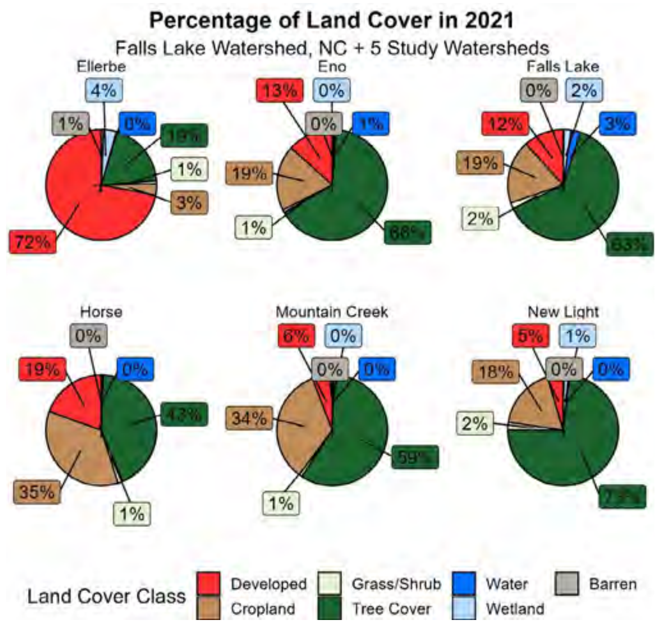
Falls Lake is a 12,410-acre reservoir in Durham, Wake, and Granville counties of North Carolina. The lake stretches 28 miles up the Neuse River to its source at the junction of Eno, Little, and Flat rivers. Its name comes from the Falls of the Neuse, which describes what used to be a whitewater section of the river between the Piedmont and the Coastal Plain and was submerged during construction of the reservoir.

The Army Corps of Engineers began building the reservoir in 1978 and completed construction in 1981. The lake was built to control damaging floods, serve as a water supply source, and protect downstream water quality during droughts. It supplies drinking water for half a million people in Raleigh, Garner, Knightdale, Roseville, Wake Forest, Wendell, and Zebulon.

Just two years after construction was finished in 1983, the lake was classified as a Nutrient Sensitive Water because it did not meet state standards for chlorophyll a in reservoirs. Chlorophyll a is a photosynthetic pigment in algae, and elevated levels indicate excessive amounts of algae, which can lead to reduced light penetration, low oxygen levels, eutrophication and nutrient imbalance in lakes. Nitrogen and phosphorous are two nutrients that algae and plants need to grow, and are often limiting factors. Management of nitrogen and phosphorous limits algal growth and decreases eutrophication.

The Falls Lake Nutrient Management Strategy was implemented in 2011 in an effort to improve water quality. The strategy, also known as the Falls Lake Rules, was developed by the Division of Water Resources and focuses first on the lower, less-polluted portion of the lake, moving upward to the poorest water quality in the upper basin. They target nutrient discharge to the lake from various sources, including stormwater runoff, wastewater treatment plants, and agriculture.

Engagement and collaboration are incredibly important for the Falls Lake study because both the UNRBA and DEQ have been working on identifying solutions for Falls Lake water quality issues for many years. The Collaboratory's Falls Lake study is intended to complement and support the previous and ongoing work. The Falls Lake study team worked closely with the UNRBA to ensure that the research did not duplicate prior efforts and addressed the most critical issues facing Falls Lake.



Percentage of land cover in 2021 for the Falls Lake watershed and five study watersheds.

Falls Lake Bathymetry, data collected 2017 (UNRBA 2019)

Falls Lake Research Summaries

What follows in the remainder of this document are summaries of the work conducted by distinct research teams addressing specific questions as part of the study. Each of these summaries contains a one-page overview and then a condensed version of the reports from each of the research teams.

To review the full technical report for each research project visit the Falls Lake Study website at: https://nutrients.web.unc.edu/

Paying for Nutrient Management $

RESEARCH QUESTIONS

1. What are the nutrient management funding strategies currently used in Falls Lake, and acknowledging the high costs of additional requirements, what other financing strategies could be used?

2. How can future Falls Lake Rules compliance be affordable? Are there existing affordability concerns? If so, how can we best mitigate those concerns?

3. Can nutrient management strategies be transferred successfully between watershed areas?

RESEARCH METHODS

From 2019 – 2023, the Environmental Finance Center (EFC) at the UNC School of Government has reviewed nutrient management literature, interviewed stakeholders affected by the requirements of the Falls Lake Rules, researched current and future financial models, and completed a Revenueshed analysis of Falls Lake. Additionally, the EFC analyzed the affordability of current financing mechanisms in Falls Lake, considered tools to mitigate affordability concerns, and investigated the obligations of Falls Lake under the Clean Water Act (CWA).

FINDINGS

In the first year of research, the EFC developed an understanding of the current financial requirements of the Falls Lake Rules and identified the existing streams of revenue used to finance rule compliance including stormwater funds, watershed protection fees, partnerships and multidisciplinary approaches, policy, and best management practices. The EFC also summarized the Upper Neuse River Basin Association's (UNRBA) background, roles, and committees, and found it to be an effective watershed management organization. In the final year of research, the EFC found that the financial impacts of a site-specific standard at Falls Lake under the Clean Water Act (CWA) were still relatively unclear, that long-term and stable funding is required to maintain the health of Falls Lake, and nutrient management strategies could be adopted from Jordan Lake recommendations and other water bodies.

MANAGEMENT IMPLICATIONS

Based on the findings from four years of research, the EFC recommended implementing additional funding mechanisms to finance nutrient management, securing long-term, stable funding, and managing the existing and emerging affordability concerns which stem from funding strategies. The EFC provided support to implement their recommendations including the Revenueshed tool, affordability metrics, and options for new policies.

RESEARCHERS

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Project Type	Total Funds Allocated	Number of Projects
Land conservation	$3,951,898	3
Green infrastructure and other best management practices (BMPs)	$964,729	8
Stormwater control measures (State-approved SCMs)	$237,179	8
Project planning and administrative costs associated with the participation in the IAIA	$162,086	2
Illicit discharge detection and elimination	$152,377	4
Programmatic measures	$21,338	4
Stream and riparian buffer restoration and enhancement	$14,074	2
Projects and activities that focus on flooding that have an associated water quality benefit	$4,846	1
Projects in greenways and parks with water quality and quantity benefits	$3,383	1
Grand Total	**$5,511,909**	**33**

2021-2022 Approved IAIA Projects and Funds

Finance Approaches to Falls Lake

To understand the current compliance with the Stage I investment-based ED requirements, the EFC identified the current credited projects and the communities that had implemented them. Credited projects were funded through investment mechanisms approved by the IAIA bylaws, with some projects having been implemented before the IAIA. With the understanding that Stage II will be more expensive than Stage I, the EFC also compiled examples of successful watershed financing methods outside of North Carolina to implement for future funding.

Current Financing Mechanisms

The projects credited under the IAIA fall broadly into five categories: stormwater funding, watershed protection fees, partnerships and multidisciplinary approaches, policy, and best management practices. These mechanisms are detailed in the paragraphs below.

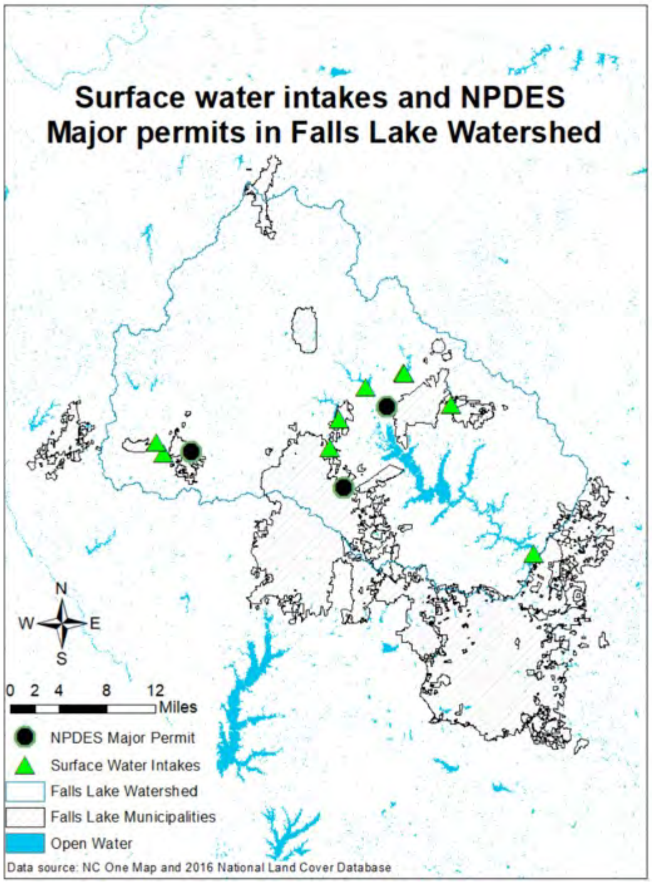
Utilities and jurisdictions with a stormwater funding mechanism included these fees on customers' water bills, in the total volumetric charge for water use, or through an annual stormwater charge like a tax. Jurisdictions with this mechanism included Hillsborough, Durham Person County, Granville County, and the cities of Creedmoor, Butner, and Stem. County and city staffs estimated that 30-100% of their stormwater funds were allocated to administrative costs and UNRBA fees.

Raleigh and Durham raised watershed protection fees to fund watershed nutrient management. Raleigh's 2011 watershed protection fee charged each water user $0.15 per 1,000 gallons to generate $2.25 million annually. With these funds and a collaboration with the Conservation Trust of North Carolina (CTNC), Raleigh protected land with the highest benefit to the Falls Lake Watershed. Durham's 2011 watershed protection structure charged customers $0.01 per CCF, raising $100,00 annually. Like Raleigh, Durham purchased land adjacent to their drinking water watersheds with the help of the Triangle J Council of Governments and the Upper Neuse Clean Water Initiative. The EFC's summary report details the barriers, benefits, and best practices for implementing these fees.

For jurisdictions without extraneous fees and funds, raising capital for nutrient management requires partnerships and multidisciplinary approaches. Partners included but are not limited to, the Soil and Water Conservation Districts (SWCD), the U.S. Department of Agriculture (USDA), the North Carolina Farm Bureau Federation (NCFBF), the Tar River Conservancy, utilities like Orange County Water and Sewer Authority (OWASA), the Clean Water State Revolving Fund (CWRSF), the Triangle Land Conservancy (TLC), various other land conservation groups, County Health Departments, School Districts, watershed improvement associations, and private landowners. Partnerships are not limited to jurisdictions lacking extraneous fees; however, governments with limited resources for funding rely heavily on these partnerships to achieve rule compliance.

All jurisdictions in the watershed adopted new policies, such as updated ordinances for new development, to comply with specific nutrient management requirements. To limit development density and protect critical areas in the Falls Lake Watershed, jurisdictions such as Raleigh increased or altered their zoning restrictions or updated their Public Utilities Handbook and Comprehensive Plan.

Beyond rates and policy, jurisdictions and farmers also pursued technical and managerial solutions. Three wastewater treatment plants (WWTP) — Hillsborough, Durham, and South Granville Water and Sewer Authority (SGWASA) — upgraded to comply with the Falls Lake Rules. Farmers have individually contributed to Rule compliance through partnerships helping them to create stream buffers and livestock exclusion areas, plant cover crops, and reduce fertilizer.



Surface water intakes and National Pollution Discharge Elimination System (NPDES) major permits. The major permits are for WWTPs in Hillsborough, Durham, and Granville County.

Future Financing Mechanisms

The current revenue streams raise enough capital for Stage I, and if expanded and added to, could also finance Stage II. The EFC studied a largely unexplored financing form called usage fees. These fees are charged to people who use environmental services provided by state, local, or federally protected areas. Programs that implement these usage fees include the Chesapeake Bay Trust Fund, License Plates, Tax Check-Off Programs, Healing, Hunting and Fishing Fund, Recreational Boating Fees via Vehicle Excise Tax, Program Open Spaces, and Voluntary Conservation Permits.

In 1985, the Maryland General Assembly approved The Chesapeake Trust Fund, which provides grant funding to projects to improve the watershed. These grant-funded projects include but are not limited to agriculture crop cover support, stormwater management, environmental organizations, watershed research, education, and technologies to accelerate bay restoration. The grants are funded by Chesapeake vehicle license plates, donations, and partnerships with private, federal, state, and local agencies.

Maryland's Chesapeake Bay license plate program sells plates at $20 and splits funds evenly between the Maryland Vehicle Association (MVA) and the Trust Fund. License plate owners reap several benefits from this program; 'accessorizing' their vehicle, personally supporting a restoration project, the ability to join the Plate Perks program to receive discounts, and prime parking at local stores. A Trust Fund survey analyzed customers' willingness to pay for the plates, finding that the plate rate was set effectively and could even be higher.

The Chesapeake Bay and Endangered Species Fund income tax check-off program also raises considerable funds for the Chesapeake Bay Trust. In 2019, the Trust raised $400,000 through individual donations from this program. In Maryland, the collected revenues are split evenly between The Chesapeake Bay Trust and the Maryland Department of Natural Resources. These types of tax revenue methods have increased in popularity. From 2002-2016, the number of US tax check-off programs almost doubled. North Carolina has several tax check-off programs, including the Nongame and Endangered Wildlife Fund. This fund, organized by the NC Wildlife Commission, uses garnered taxes monies to complete nongame conservation projects for nongame animals. Approximately $11 million have been donated this way since 1984.

The Healing, Hunting, and Fishing Fund is a partnership between three organizations—the Chesapeake Bay Trust Fund, The Chesapeake and Atlantic Coastal Bays Trust Fund, and the Maryland Department of Natural Resources (MDNR). Individuals purchasing a hunting, fishing, or boating license through the MDNR's online portal can choose to donate to this fund. As established by the Maryland General Assembly, the Chesapeake Bay Trust can use these funds for grants that result in specific habitat outcomes outlined by the General Assembly, including water quality protection.

The Maryland Waterway Improvement Fund (WIF), managed by the MDNR, uses Vessel Excise Tax (VET) to fund grants for projects that protect surrounding waters. Annual revenues from the VET range from $15 million to $31 million and fluctuate with economic health. The VET taxes all vessels that are primarily used in Maryland waters and therefore can include registered boaters from out of state. The VET is a one-time charge set at 5% of the boat's net purchase price. The VET has a floor tax of $5 and a ceiling tax of $15,100, impacting boats outside the $100 to $302,000 range.

Studies indicated that the ceiling tax increased sales of higher-valued boats. The funding structure for Maryland's Program Open Spaces (POS) tax directly links development to dollars raised for open lands and subsequently healthy water quality. POS dollars fund protected land acquisition and Greenway and Green Infrastructure projects. The General Assembly approved a real estate transfer tax that charges 5% on every real estate transaction in Maryland. Seventy-five percent of the real estate tax is allocated to fully fund the POS.

As a result of POS's success, 394,000 acres of land are protected, and most Maryland citizens live within 15 minutes from POS land. It has been well established that land use directly impacts water quality, particularly land cover. If Falls Lake were to implement a similar program, a vote would be required as North Carolina state statutes order a vote for publicly funded conservation projects.

The Pennsylvania Fish and Boat Commission has succeeded tremendously with its Voluntary Habitat/Conservation Permit program raising $129,850 through 7,000 permit sales in 2020. The commission raises funds through permit sales for trout, bass, muskies, and habitat/waterway conservation. Dollars are only used to finance projects related to fish habitat, research, and stream improvement. The Falls Lake Watershed could benefit from implementing all permits, but most notably from the Voluntary Habitat/Waterways conservation. This permit's funds specifically strengthen aquatic habitats by creating riparian buffers, decreasing erosion, and improving water quality.

Site Specific Standard

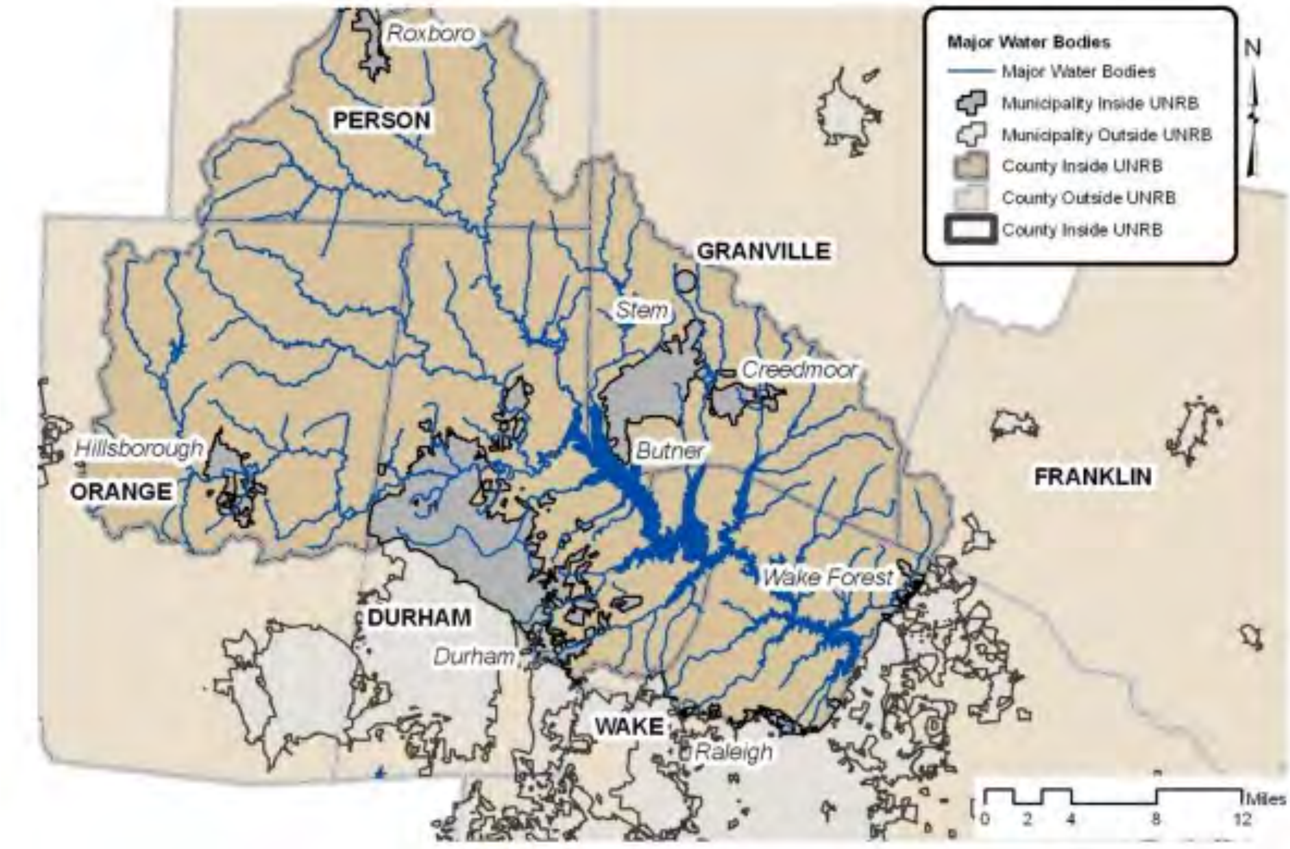
The UNRBA addresses both the anticipated cost burdens and an inability to reach the state's chlorophyll-a limit with its proposal to the DWR for a site-specific standard at Falls Lake. A site-specific standard must meet two criteria. First, it cannot alter a water body's designated use, and second, it must be an environmental indicator. A future site-specific standard would most likely use chlorophyll-a, as it satisfies the criteria mentioned above. Before adoption, all proposed rules must undergo a Regulatory Impact Analysis to ensure compliance with North Carolina state law. The process includes analysis of unnecessary and unduly burdensome policies to ensure fair treatment of state citizens.

North Carolina has approved chlorophyll-a site-specific standards, including one at High Rock Lake in 2019. Due to the similar regulatory structure between High Rock and Falls Lakes, the EFC used the financial impacts and Regulatory Impact Analysis outcomes at High Rock to anticipate outcomes at Falls Lake. Based on the results, the EFC anticipated the Regulatory Impact Analysis for the proposal of a site-specific standard at Falls Lake would report no financial impact. Implementation of the proposed rule would create financial impacts, however.

As the cost for the proposed rule would be $0- under the outlined $1 million limit- the EFC anticipated that no fiscal note would be required. Even with the site-specific standard, it is unknown if High Rock Lake or Falls Lake will be taken off the 303(d) impaired waters list. The DWR is working with the EPA to incorporate site-specific standard considerations when compiling the list. While implementation costs are unknown, the UNRBA continues petitioning for a site standard with additional flexibilities.

Revenueshed Approach

The EFC defines a Revenueshed as the area within which revenue is generated for a specific purpose. In Falls Lake, a Revenueshed approach could be used to raise funds for watershed protection. The approach aims to expand beyond the polluter pays model, allowing impactors and beneficiaries to contribute financially to water quality protection. Additionally, the model mitigates issues caused by misaligned water and jurisdictional boundaries such as free-riding, reactive water quality protection, complexities with financing multiple watersheds, and the lack of a comprehensive polluter pays model.



Map of Upper Neuse River Basin showing county and municipal boundaries do not align with watershed boundaries.

The issue of free-riding and reactive water quality protection arises when multiple jurisdictions are part of, and therefore responsible, for maintaining water quality. All jurisdictions want clean water but do not want to finance the initiative alone. Furthermore, organizing a pooled revenue for water quality is difficult, which can increase hesitancy to participate in a pooled revenue program. This leads to a reactive policy if direct aid to water quality is not addressed until it reaches a crisis point or a regulatory entity necessitates action. To further complicate the issue, one jurisdiction can rely on and be a part of multiple watersheds, which is expensive and complex. Many watersheds are subject to unique legislative requirements; Durham and Orange County are subject to Jordan Lake and Falls Lake Rules.

Lastly, with the lack of an encompassing polluter pays model, not all upstream users are charged for their pollution, and downstream users suffer the environmental and financial consequences of poor water quality. For example, only counties in the Falls Lake watershed contribute to the IAIA; however, counties outside Falls Lake pollute the watershed through runoff.

To help the Falls Lake Watershed communities manage pooled resources for water quality improvement, the UNC EFC developed a Revenueshed Tool that visualizes generated funds within the watershed based on inputted project goals with manipulatable revenue streams. The Falls Lake Revenueshed Tool presents data meant to guide political decisions in and between jurisdictions to leverage this taxable value for watershed protection and mitigate complexities from financing watershed management. The model combines utility rates, property tax, consumption, and affordability metrics to model how small bill increases across the watershed can generate substantial revenue. The full-length Falls Lake Nutrient Study Report provides a detailed description of the tool and where it is available for public use.

The full Paying for Nutrient Management report can be found at: [*https://nutrients.web.unc.edu/*](https://nutrients.web.unc.edu/)

Policy in Focus: Costs to Local Governments

As with all legal matters, an understanding of the legal framework is important when evaluating the equity principles that apply to imposing liability on any person, including a local government. The Falls Lake rules are the only set of rules in North Carolina that impose the responsibility to reduce nutrient loading from existing development on local governments within their respective jurisdictions regardless of the source of the nutrients being discharged.

This rule requires determining the amount of nutrient loading at the boundaries of jurisdiction. Accordingly, the classifications of nutrients include natural sources (such as forests), fallow lands, overflows or discharges from stormwater control measures, groundwater recharge burdened with nitrogen from historic land uses, and overflows not controlled by agricultural measures to address nutrient loading. Thus, the rule uniquely imposes on the local governments the obligation to address nutrient loading regardless of who owns the property or whether the legislature has authorized the local government to regulate the source of the loading.

This rule does not rely on specific legislative authority to impose legal liability for the cleanup of pollutants by the local government because it is the location from which the nutrient loading arises. The historic approach to sources that are naturally occurring or outside the control of the party being assessed is to address the costs from environmental taxes imposed on benefitting resource users or the primary government's general population. i.e. the State.

In its prior work on the readoption of the Falls rules, the N.C. Environmental Finance Center developed a list of existing authorities by which local governments could finance the cost of these remedial efforts. The DWR projected collective cost of the reductions stands at $1.54 billion, with a cost of $606.3 million by 2024. Because the requirement is found in the rules of the N.C. Environmental Management Commission, the requirement is enforceable as a part of the stormwater system permit issued to each local government in the Falls Lake Basin. As part of an NPDES (National Pollution Discharge Elimination Permit), it can also be enforced by citizen suits under the federal Clean Water Act even though the current Clean Water statutes were adopted before stormwater was regulated under the federal Clean Water Act.

This research looks more closely at the sources of authority identified by the Environmental Finance Center, and in particular, at the limitations or impediments that arise with each suggested approach for additional sources of revenue to fund the requirements of the current rule. Given the legal limitations on the proposed revenue sources one conclusion is that the most effective means to address this fiscal need is by a tax to be levied by the General Assembly on the users of the drinking water supplied from Falls Lake.

A primary benefit of the nutrient reductions in Falls Lake is improved quality of the drinking water supply at no cost to the more than 600,000 users of Raleigh Water. It is important to note

City of Raleigh Intake in Falls Lake.

that the nutrient loading budget included groundwater recharge as a source of jurisdiction loading. As currently applied, the non-point source cost allocation scheme is inequitable and should be amended. Both reservoirs were constructed for the designated purpose of providing a drinking water supply. When the reservoirs are used as a drinking water supply, there is a substantial economic benefit to the local government using the reservoir for its drinking water supply.

When the benefiting local governments are located near the dam for the reservoirs, their responsibility for assisting in the cost of the remedial actions is substantially smaller than the benefit enjoyed from the drinking water supply which is improved in quality by the remedial regulatory scheme. Consequently, the upstream local governments, with limited or no access to the drinking water supply, have a disproportionate cost for the implementation of the remedial program. That substantial inequity should be addressed, especially as it arises from the requirement to reduce loading from sources outside the direct control of the upstream local governments.

An equitable means to address this problem, in part, is a tax on the water users who rely upon the waterbody.

This Policy in Focus: Costs to Local Governments is a summary of research conducted by Dan McLawhorn, a legal and policy consultant for the Falls Lake Study.

The full report can be found at: https://nutrients.web.unc.edu/

Scientific Review of Watershed and Water Quality Modeling

RESEARCH QUESTIONS

The Upper Neuse River Basin Association (UNRBA) has been developing a suite of models to better understand the feasibility of improving water quality, particularly through watershed nutrient management. In light of these new models, this study questioned the feasibility of improving water quality, particularly through watershed nutrient management.

RESEARCH METHODS

In this study, the research team supplied review and input to the UNRBA modeling effort in the context of related scientific literature, considering model setup, forcing data, biophysical rates, and simulation results. Particular attention was paid to nitrogen (N) and phosphorus (P) dynamics, as nutrients are key drivers of eutrophication in most reservoirs. Specifically, this effort investigated the benefits of management actions over different spatial and temporal scales.

FINDINGS

Atmospheric deposition and internal sediment nutrient fluxes were both found to be substantial sources of nutrient loading to Falls Lake. This study provided a scientific literature review on nutrient deposition, with an emphasis on studies/results relevant to central North Carolina. These findings characterize the spatio-temporal variability in N deposition with a relatively high level of confidence. P deposition was relatively uncertain, though it is also a relatively small source (compared to other P sources in the watershed). Additionally, this study led to the development of a literature review of typical phosphorus and nitrogen internal flux rates, focusing on comparable water bodies, that informed UNRBA model calibrations.

An unexpected finding that the initial UNRBA watershed modeling results indicated similar loading rates from developed and undeveloped lands led to the creation of a literature review of typical nutrient loading rates from other comparable studies. This review details that nutrient loading rates from developed lands are typically several times higher than from undeveloped lands. The review helped motivate updates to the model calibration, resulting in a more realistic nutrient source apportionment.

MANAGEMENT IMPLICATIONS

The review also highlights the need to consider how atmospheric deposition will respond to changes in local watershed development/activities. In future efforts, additional adjustments to the watershed model and/or model development process may be beneficial.

Given the uncertainties associated with internal loading, and consistent with principles of adaptive management, additional monitoring and model updating may be advantageous for constraining uncertainties in these fluxes and better anticipating how the lake will respond to changes in nutrient loading over the long term. If internal loading is higher than the modeled rates, then stakeholders may need to wait longer than expected before they will see water quality improvements (following any watershed loading reductions).

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Modeling Review

Falls Lake is a critical water supply reservoir for central North Carolina (NC). Water quality in the reservoir is affected by anthropogenic nutrient loading, contributing to high algal levels (chlorophyll concentrations) and other concerns associated with eutrophication (e.g., hypoxia, potential for cyanotoxins). The Upper Neuse River Basin Association (UNRBA) has been developing a suite of models to better understand the feasibility of improving water quality, particularly through watershed nutrient management. These models can assess the benefits of management actions over different spatial and temporal scales.

Like all environmental models, the UNRBA models provide an approximate representation of water quality processes and incorporate numerous assumptions related to uncertainties in model structure and biophysical rates. In this study, we provided review and input to the UNRBA modeling effort in the context of related scientific literature, considering model setup, forcing data, biophysical rates, and simulation results. Particular attention was paid to nitrogen (N) and phosphorus (P) dynamics, as nutrients are key drivers of eutrophication in most reservoirs.

Atmospheric nutrient deposition is a major driver of the UNRBA's watershed model (WARMF-watershed) and ultimately the lake response. Understanding reasonable rates and uncertainties in nutrient deposition is important for developing reliable and interpretable results. To this end, we provided a scientific literature review on nutrient deposition, with an emphasis on studies/results relevant to central NC. We were able to characterize spatio-temporal variability in N deposition with a relatively high level of confidence. P deposition was relatively uncertain, though it is also a relatively small source (relative to other P sources in the watershed). This information informed UNRBA model and scenario development. The review also highlights the need to consider how atmospheric deposition will respond to changes in local watershed development/activities.

Internal nutrient fluxes from reservoir bottom sediments are another driver of lake water quality. Internal loading provides a long-term supply of nutrients that can delay the benefits of external (watershed) loading reduction. Thus, we developed a literature review of typical phosphorus and nitrogen internal flux rates, focusing on comparable waterbodies, that informed UNRBA model calibrations.

At the same time, the wide range of flux estimates suggests that considerable uncertainties remain. Consistent with principles of adaptive management, additional monitoring and model updating may be advantageous for constraining uncertainties in these fluxes and better anticipating rates of lake water quality improvement/decline in response to changing nutrient loads.

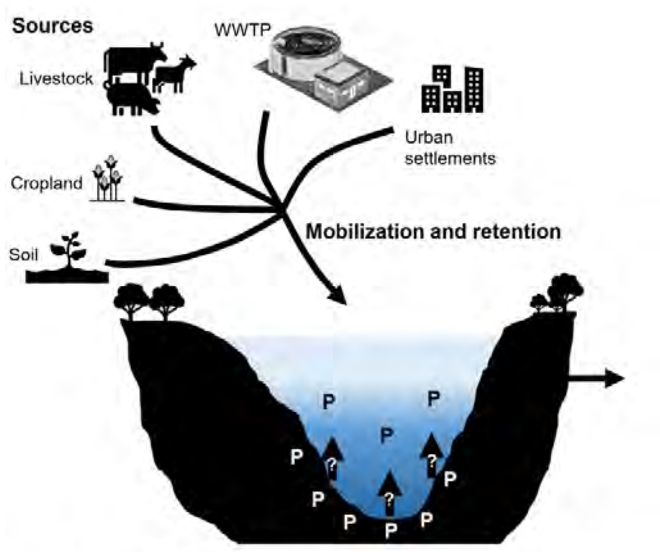


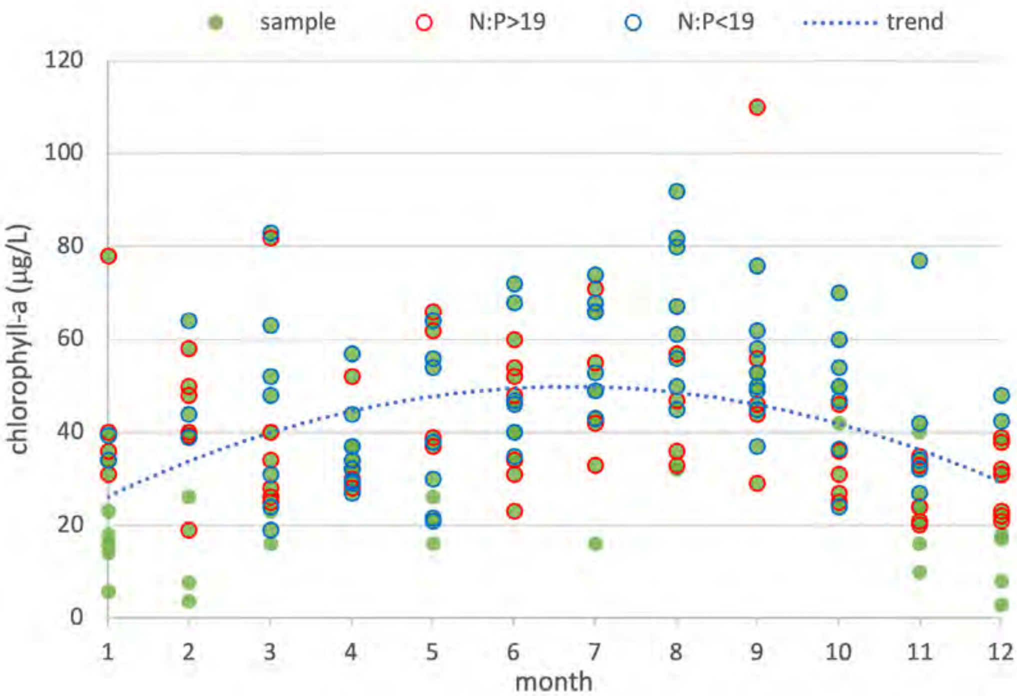
Fig : Various sources of P loading to a lake or reservoir

Characterizing nutrient loading rates from various land uses, such as urban, agricultural, and forest, can help inform the development of realistic and effective watershed management strategies. Initial UNRBA watershed modeling results indicated similar loading rates from developed and undeveloped lands, which was unexpected.

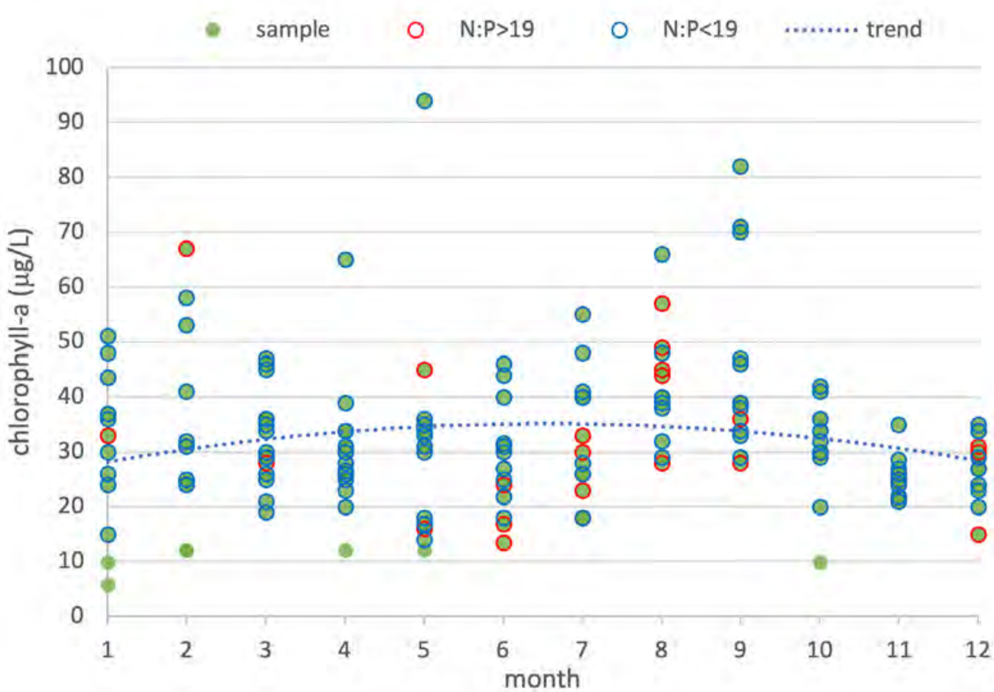
Thus, we developed a literature review of typical nutrient loading rates from other comparable studies. We found that nutrient loading rates from developed lands are typically several times higher than from undeveloped lands. This information helped motivate an update of the model calibration, but remaining uncertainties should be considered when applying the model to various management scenarios.

In addition to the research items listed above, another substantial component of this project was to provide a more general review of the model development process and address various questions and issues that arose throughout this process.

Station NEU013B (Upper Falls Lake): Chlorophyll Concentrations by Month with Indications of Nutrient Limitation



Station NEU018E (Middle Falls Lake): Chlorophyll Concentrations by Month with Indications of Nutrient Limitation



Atmospheric Nutrient Deposition

To help support the modeling effort, we provided a review of atmospheric nutrient deposition estimates from various academic and governmental sources. Our complete reports on nitrogen and phosphorus deposition can be found in our year 1 and year 2 project reports, respectively.

A summary of key findings is provided below:

Nitrogen Deposition:

• The median total annual N deposition for the study area is 12 kg/ha/y.

• Spatially distributed estimates of total N deposition (for 2010-2012) typically range from 9-13 kg/ha/y across the study area, with higher values in urban areas.

• Total N deposition is highest in summer, followed by spring, mainly due to higher precipitation in our study area during these seasons.

• Total annual N deposition is positively correlated with annual precipitation. This is primarily due to precipitation increasing wet deposition.

• Dry N deposition makes up about 60% of total deposition.

• Total N deposition is higher in urban areas, primarily due to higher dry oxidized deposition; and in intensive livestock areas (southeast NC), primarily due to higher dry reduced N deposition.

• Oxidized N accounts for about 40% of wet deposition, 80% of dry deposition, and 65% of total deposition.

Phosphorus Deposition:

• There is less reliable monitoring data for P deposition relative to N deposition.

• Estimates of atmospheric TP deposition vary widely across different studies. In the U.S., estimates typically range from 0.05 to 0.5 kg/ha/yr.

• In a recent EPA study, atmospheric TP deposition for the Falls Lake Basin was approximately at 0.08 kg/ha/yr in 2012, but with notable uncertainty.

• In most studies, dry TP deposition exceeds wet TP deposition.

• Temporal variability in P deposition may be driven by precipitation and agricultural activities.

• Higher P deposition is often found in agricultural areas but trends with urbanization are less clear across studies.

These reports informed watershed model calibration and are included in the appendices of the UNRBA watershed modeling report. These reports also demonstrate how a significant portion of deposition (particularly N deposition) is derived from local sources, which should be considered in the modeling of future scenarios.

While P deposition rates are quite small relative to N deposition rates (N:P ~ 100 by mass), the large uncertainty in P deposition rates suggests that additional monitoring of this source may be beneficial.

Internal Nutrient Fluxes

Recycling of nutrients from the reservoir bottom sediments can represent a large fraction of the total nutrient input to a waterbody. Such recycling can delay benefits from external (watershed) mitigation efforts. This source is often referred to as “internal loading”, though it may reflect the accumulation of external loads over long time periods. To inform the modeling effort, we provided a review of internal loading estimates from similar lakes and reservoirs around the country. Our complete reports on phosphorus and nitrogen internal loading can be found in our year 1 and year 2 project reports, respectively.

A summary of key findings is provided below:

Nitrogen Internal Loading:

• Measurements of internal N fluxes are less common than internal P flux measurement.

• Measurement of internal N fluxes under anaerobic conditions typically range from 0.6 to 3.0 g/m2/month in eutrophic lakes and reservoirs. Anaerobic conditions are most prevalent in summer, when warmer temperatures also increase ammonia flux rates.

The internal loading of Falls Lake is a key factor to consider during the management process.

・Measurements of internal N fluxes under aerobic conditions typically range from 0 to 2.5 g/m2/month.

・The above estimates are for ammonia-N, which is the dominant form of N released by sediments.

・Nitrate-N is lost at the sediment layer due to denitrification, and this can offset the ammonia release to varying degrees (literature estimates vary widely).

• These measurements do not include all N release mechanisms, such as resuspension of sediment/benthic material during wind-mixing events.

• Our modeling study of Jordan Lake indicated internal N fluxes of around 10 g/m2/month in summer and 2 g/m2/month in winter (averaged across the lake), which are above typical literature values (but not without precedent in warm eutrophic systems).

• N flux estimates (from measurement studies) for Falls Lake generally suggest fluxes of 1-5 g/m2/month as ammonia in summer. Nitrate-N fluxes were generally small or negative. Ammonia fluxes were typically highest in downstream monitoring locations, where sediments tend to accumulate and hypoxic water conditions are most common.

Phosphorus Internal Loading:

• Measurements of internal P fluxes under anaerobic conditions typically range from 0 to 1.2 g/m2/month in eutrophic lakes and reservoirs. Anaerobic conditions are most prevalent in summer.

• Measurements of internal P fluxes under aerobic conditions are typically under 0.2 g/m2/month.

• These measurements do not include all P release mechanisms, such as resuspension of sediment/benthic material during wind-mixing events.

• Our modeling study of Jordan Lake indicated internal P fluxes of around 0.5 g/m2/month in summer and 0.1 g/m2/month in winter (averaged across the lake), generally consistent with the literature review.

• A wide range of internal P flux estimates (from measurement studies) have been reported for Falls Lake. While one study indicated values similar to our estimates for Jordan Lake, another suggests lower values.

Overall, this literature review suggests that internal loading is a substantial nutrient source for Falls Lake. However, preliminary UNRBA model simulations suggested relatively small internal fluxes. As these simulations are dependent on numerous parameters that are imprecisely known, there was room to make adjustments to the model calibration. Based partly on this review, UNRBA modelers were able to increase nutrient fluxes to be more consistent with literature expectations. In addition, UNRBA modelers conducted additional model simulations to test the sensitivity of phosphorus fluxes to various model parameters.

While simulated fluxes did increase through model refinement, they remain on the low end of literature ranges. Several possible reasons were discussed, including a very thin sediment layer present throughout much of the upstream half of the reservoir. It is also possible that reservoir sediments may contain high levels of P-binding elements (e.g., aluminum), which appears plausible based on USGS geochemical soil maps. Given the uncertainties associated with internal loading, and consistent with principles of adaptive management, additional monitoring and model updating may be advantageous for constraining uncertainties in these fluxes and better anticipating how the lake will respond to changes in nutrient loading over the long term. If internal loading is higher than the modeled rates, then stakeholders may need to wait longer than expected before they will see water quality improvements (following any watershed loading reductions).

Note that our Jordan Lake modeling results were presented at the Falls Lake Nutrient Management Study Research Symposia, Chapel Hill, NC, in May 2021 and April 2023. The 2021 presentation included a more general discussion of different modeling approaches, while the 2023 presentation included a more detailed discussion of nutrient flux estimates, including a comparison with those in Falls Lake.

Nutrient Fluxes From Urban Versus Undeveloped Lands

Anthropogenic activities, such as urban development and agriculture, are expected to increase watershed nutrient export. This is largely due to increased fertilizer use and erosion in developed or developing areas. Other factors like pet waste and leaking sewage infrastructure may also contribute.

From November 2021 to January 2022, there were a series of meetings and correspondences with UNRBA staff/modelers regarding the nutrient source apportionment of the WARMF-watershed model. Results suggested similar levels of nutrient export (per unit area) from undeveloped (e.g., forest) and urban lands. To explore this issue from a broader perspective, we compared nutrient loading rates from urban and undeveloped lands based on other studies in the region. This review, which is contained in our year 2 report, suggests that urban areas export 4-12 and 2-8 times more TP and TN, respectively, than undeveloped lands.

The research team's independent modeling of the Falls and Jordan Lake watersheds also suggested that urban nutrient loading rates are several times higher than forest loading rates, and this research was presented at the Falls Lake Nutrient Management Study Research Symposium, Chapel Hill, NC, April 2022.

Motivated in part by this review, the model calibration was updated by extending the model warmup (or spin-up) period so that soil processes and nutrient export could better equilibrate with nutrient inputs, resulting in greater differences between urban and undeveloped land export. The presentation of source apportionment results was also updated to highlight the role of streambank erosion in urban phosphorus export, which is tracked as a separate category in the WARMF-watershed model.

In the finalized model, the urban:forest loading ratio is estimated to be about 1.7 and 1.1 for TN and TP, respectively. If streambank erosion is assumed to occur largely (say 80%) in developed areas, then these ratios increase to around 2:1 for both TN and TP.

To help justify the calibration, UNRBA staff/modelers note that approximately 90 percent of "urban" land in the Falls Lake watershed is low intensity development or developed open space (both have an assumed percent imperviousness of 20 percent). To comply with the Falls Lake Rules, local governments have installed over 350 development retrofit projects.

For these reasons, urban export in the Falls Lake watershed may be lower than in historical studies of areas with limited BMPs (or in studies that discount BMPs). Also, the WARMF-watershed model only readily provides nutrient loads to Falls Lake after being subject to removal/retention in upstream water bodies; and the predominantly forested lands around the edge of the reservoir have less opportunity for removal/retention.

At the same time, constraints in the model formulation may also limit the model's ability to fully differentiate the loading rates associated with different land use types. For example, the same hydraulic conductivity is assigned throughout a subwatershed regardless of variations in land use type. Such limitations should probably be addressed when the model is applied to alternative future (or past) land use scenarios. This issue came up in 2023, when the model was applied to an "all-forest" scenario. When these issues were identified, UNRBA modelers adjusted hydraulic conductivities to some extent.

However, since hydraulic conductivity was treated as a calibration parameter (rate) in model development (rather than as a function of soil properties), a more rigorous adjustment was not readily available, especially within UNRBA timeline and budget constraints. Other factors, such as the variability in soil denitrification rates used in the model, may also warrant attention when producing and interpreting various model scenarios.

These issues highlight the potential benefits of model parameters and results that are readily comparable to literature values. UNRBA provided this to the extent possible, given project constraints. In future efforts, additional adjustments to the watershed model and/or model development process may be beneficial. Note that some of these issues were addressed in a review of the UNRBA draft watershed modeling report.

The full Scientific Review of Watershed and Water Quality Modeling can be found at: https://nutrients.web.unc.edu/

Policy in Focus: Upper Neuse River Basin Association Modeling Efforts

During the course of the Falls Lake Study the work of the Upper Neuse River Basin Association (UNRBA) has helped inform research questions and their independent research and evaluation is a valuable component that goes hand in hand with much of the work of the Collaboratory study. Below is a summary of the UNRBA's Watershed Modeling Report.

Modeling Approach

In an effort to inform new and improved nutrient reduction strategies for Falls Lake the UNRBA devised a plan to monitor water quality from 2014 to 2018, using scientific research and the Watershed Analysis Risk Management Framework (WARMF). The WARMF Watershed Model is a well-established, tested, and accepted tool for the development of realistic and viable results that can effectively guide the development of a regulatory approach to address reservoir nutrient impacts. In using this model to conduct scientific research, they have been able to reevaluate previous water quality standards and discover findings that can inform future decisions about nutrient management strategies for Falls Lake.
The Falls Lake WARMF model works by simulating the movement of applied nutrients over the land surface, through the soil, and through streams and impoundments to Falls Lake. Within the model, most sources of nutrients that are applied or released to the Falls Lake watershed are represented using model input files such as atmospheric deposition, nutrient application to agriculture or urban land, wastewater treatment facilities, sanitary sewer overflows, and onsite wastewater treatment systems. Data illustrating the nutrient load from these different sources are categorized, tracked, and calculated by the model.

Sources of Nutrient Loading

The WARMF model identified the various sources of nutrient loading into Falls Lake and the magnitude of their contributions, looking primarily at levels of TP (Total Phosphorus) and TN (Total Nitrogen). Atmospheric deposition and nutrient application to agricultural and developed areas are the largest gross contributors to TN and TP in the watershed. They each contribute approximately 40% of the TN applied to the WARMF system. Nutrient application to agriculture and fertilizer application to urban areas contribute approximately 60% and 20% of the TP load applied to the system, respectively. Urban areas, which comprise only 13% of the watershed, are the next highest contributors to nutrient loading, contributing 14.7% of TN, 10.6% of TP, and 11% of Total Organic Carbon. All other sources' nutrient contributions are relatively low. Onsite wastewater treatment systems contribute only 2% or less, and major wastewater treatment plants contribute less than 6% of TN and approximately 3% of TP.

Importance of Hydrologic Cycle

Unmanaged lands comprise approximately 75% of the land within the watershed and contribute about half of the delivered nutrient and carbon load to Falls Lake. 38.1% of Total Nitrogen (TN) and 43.9% of Total Phosphorus (TP) delivered to the lake originate from unmanaged lands. Throughout the study, the WARMF model helped researchers discover that the amount of rainfall and the hydrologic cycle play a significant role in determining the amount of nutrient load that reaches the lake, particularly regarding unmanaged lands.

These pervious areas in the watershed that receive inputs from atmospheric deposition and nutrient application can store nutrients in the soil during dry periods. During wet periods when the soils become saturated, these nutrients have the potential to be transported to the stream network and Falls Lake. Large storms and days with heavy rain can increase delivered nutrient loads by hundreds of times compared to days with little to no rainfall. The hydrologic cycle plays a significant role in the nutrient load to Falls Lake from unmanaged lands, which must be considered when devising future management strategies.

While they contribute significantly to nutrient loading, unmanaged lands are also incredibly important to the health of the watershed and the lake. They store and cycle nutrients and carbon, infiltrate and store rainwater, buffer temperatures, and provide habitat to terrestrial, avian, and aquatic wildlife. In the recent study period, the watershed modeling showed that only 19% of the TN applied/

released in the watershed reaches Falls Lake. Thus, the modeling demonstrates that watershed processes and activities in the watershed effectively reduce the loading applied/released in the watershed by 81%. The conservation of unmanaged lands is a vital component of future revised long-term nutrient management strategies.

The UNRBA's study revealed that previous nutrient reduction standards for Falls Lake were unattainable—a new nutrient management strategy must account for this and set more plausible reduction standards. Stage II of the 2011 Falls Lake Nutrient Management Strategy requires a 77% reduction in TP load delivered to the lake from agriculture, wastewater, and existing development relative to the baseline period (2005-2007). However, reducing loading to Falls Lake from the land uses by 77% is unachievable. Additionally, the chemistry of the soils in the watershed results in the retention and slow release of nutrients overtime. This means that changes in the watershed directed at nutrient management may take decades to have a measurable impact on nutrient loading to Falls Lake. It will be important to consider this time frame in future management strategies and ensure reduction standards within it are attainable.

UNRBA members, stakeholders, and other regulatory entities have played a significant role in prior nutrient management control measures, and their contributions will be important for the implementation of future reduction strategies. Beginning shortly after the Falls Lake Nutrient Management Strategy was passed in 2011, some UNRBA members and regulated entities took measures such as installing hundreds of stormwater control measures and implementing stream restoration projects to improve water quality and reduce nutrient loading to the lake.

Additionally, UNRBA members have also provided extensive investments to secure improvements at wastewater treatment plants, reductions to sanitary sewer overflows, implementation of retrofits for existing development, and maintenance and repair programs for onsite wastewater treatment plants. These efforts required significant support and funding, and stakeholders' resources were vital in the reduction of nutrients since 2011. Thus, the responsibility of nutrient reduction has not and will continue not to rest on one entity, but on a variety of different players. Both internal and external stakeholders, including, but not limited to local governments, utilities, and the agricultural community, have a vested interest in reducing the nutrient load and will have to make important contributions to these efforts in terms of funding, aiding in implementation of new infrastructure and regulation, etc.

For more information about the modeling work of UNRBA visit: https://unrba.org/

In Situ Observation of Falls Lake: Circulation and Physical Characteristics

RESEARCH QUESTIONS

1. What are the primary circulation patterns and physical structures in the main channel and in the large side arms (i.e., Little Lick Creek, Ledge Creek and Lick Creek) of the lake? How do these properties vary as functions of inflows, outflows, meteorology, physical properties, and the seasons?

2. How and to what significance do the side arms interact with the flow along the main stem of the lake?

RESEARCH METHODS

Researchers from the UNC-CH Institute of Marine Sciences and Department of Earth, Marine & Environmental Sciences performed a four-year In Situ Observational Study of Falls Lake, comprising of two phases. Phase one (years 1 and 2) detailed the primary influences on water circulation patterns, flow structures, and residence times (the mean times that water spends in the lake) along the river-like main stem of the lake. Phase two (years 3 and 4) focused on the flow through three side arms located in the nutrient sensitive portion of the lake. Research questions were addressed by collecting long-term observational data using water current monitoring tools and temperature/light/conductivity sensors at strategic locations throughout the lake.

FINDINGS

Results from phase one demonstrated that the strongest flows are a response to lake level variations. Rapid increases in water level are accompanied by large but brief currents in the upper portions of the lake. When the lake level is constant or slowly falling, currents are slower and can vary in magnitude and direction with depth. The surface flow of the lake often moves in the same direction as the wind. Key features of the main stem are a wind-driven exchange flow, created by a reversal of the current direction at mid-depth or below flowing in the opposite direction of the surface flow, and a 5.5-hour natural oscillation of the lake. Residence times are highly variable, as short as weeks and as long as 5 years (median = 4.75 months). The strength of stratification (the rate of change of temperature with depth), averaged seasonally, was consistent between the 3 testing sites, and reached a maximum of approximately 1 °C/m during the summer. Analysis of the phase two observations found flow in the side arms was substantially different from the main stem and from each other. The side arms did not show a strong response to the 5.5-hour oscillation seen in the main stem, but responded strongly to wind force. Circulation was strongest in Lick Creek, moderate in Ledge Creek and least in Little Lick Creek. Winds contributed to the exchange of water with the main stem, driving surface currents in the direction of the wind and in the opposite direction in the deeper portion, creating an exchange flow that was more regular and sustained during warmer months. Residence times in the side arms due to the exchange flow vary between 4.6 to 16.4 days, with the shorter residence times more common during the summer months.

MANAGEMENT IMPLICATIONS

These results document the character of water circulation in Falls Lake. From a management perspective, as times of slow flow are typically associated with poor water quality, attention to flow during these times is particularly warranted. These findings have increased the understanding of transport in Falls Lake and can serve as important validation of water quality modeling efforts, such as those sponsored by the UNRBA. Temperature and in vivo fluorescence (a measure of chlorophyll-a and related biomass) showed significant spatial variability, however, there were no discernable patterns that were identified.

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Background

Falls Lake is a man-made reservoir, constructed by the US Army Corps of Engineers (USACE) from 1978 to 1981. The lake is 28 miles long from the confluence of the Eno, Little and Flat rivers to the dam and comprises approximately 12,400 acres of open water. Highway 50 divides the lake's volume approximately in half; the upper section is shallower and wide in comparison to the deeper, narrower lower section that follows the historical river channel. The main stem is segmented by six causeways: railroad, I85, Fish Dam Rd, Hwy 50, New Light Rd, and Hwy 98 from upstream to downstream.

Net flow through the lake's main stem is principally determined by tributary inputs and the outflow over the dam. The lake has at least 18 tributaries, of which five, the Flat River, Eno River, Little River, Knap of Reeds Creek, and Ellerbe Creek, contribute an average of 78 percent of the annual inflow, (UNRBA 2019). No other tributary delivers more than 3 percent of the annual inflow. All five of the major tributaries enter the lake upstream of the Interstate 85 crossing. Outflow from the lake comprises the Neuse River and is controlled by the USACE for flood control in the Neuse Basin, drinking water supply, recreation, fish and wildlife enhancement and water-quality control, (USACE 2013).

The NC Division of Water Resources (DWR) has collected water quality data in the lake since its opening. Chlorophyll-a concentrations in excess of 40 micrograms per liter in portions of the lake prompted a modeling study in the 2000s to help identify nutrient reduction targets and the establishment of strategies in 2010 to reduce nutrient input to the lake. To supplement DWR efforts, in 2014 the Upper Neuse River Basin Association (UNRBA) initiated an extensive data collection and analysis program in the lake and its tributaries (UNRBA 2019) and a re-modeling of the lake (UNRBA 2016a). Water quality data has also been collected in the lake by the City of Durham and by the NC State University Center for Applied Aquatic Ecology (CAAE).

Lake water quality is influenced by multiple factors, including the movement of water and associated constituents (nutrients, sediments, algae, etc.) through the system. Residence time provides a lake-wide average assessment of water movement. From August 2014 – November 2018, the UNRBA found residence times (computed as 15-day average lake volume divided by the 15-day average outflow over the dam) varied from as little as 20 days to nearly 2.5 years, with long residence times occurring when the USACE reduced outflow for downstream flood control (UNRBA 2019).

Different types of equipment and monitoring devices were deployed in Falls Lake as part of the research.

To better document the lake's response to high-flow conditions (which are infrequent but account for a significant portion of the volume inflow to the lake), the UNRBA also sponsored one-hour long flow measurements at the I85 and Hwy 50 causeways, on four days in January and October 2016. Results were converted to daily average discharge and appeared to track predictions based on a mass balance that included changes in lake surface elevation, rainfall, tributary inflows, and evaporation estimates (UNRBA 2016b; UNRBA 2017).

While water quality is strongly dependent on the inflows to and outflow from the lake and the associated average transport through the lake, the timescales of nutrient uptake, primary productivity and algal growth are fast compared to average transport timescales. Indeed, the relationship between short-term hydrodynamics and productivity has been identified as having important implications for the lake's water quality model (UNRBA 2015), although no systematic effort has been undertaken to measure water movement in the lake at these scales

Furthermore, no data or analyses have been undertaken to identify circulation and exchange within the lake. Specifically, several substantial tributaries enter the lake below Fish Dam / Cheek Rd. These "side arms" have substantial surface area but relatively low inflow volumes from the watershed. Lacking significant inflow, it is unclear what the dominant circulation drivers, flow structure and resident times are in these portions of the lake and how they interact with the along-lake flow. Thus it is also unclear whether they may have a significant role in nutrient processing, algal growth and water quality in the lake.

To address these data and knowledge gaps, our study was designed around the following questions:

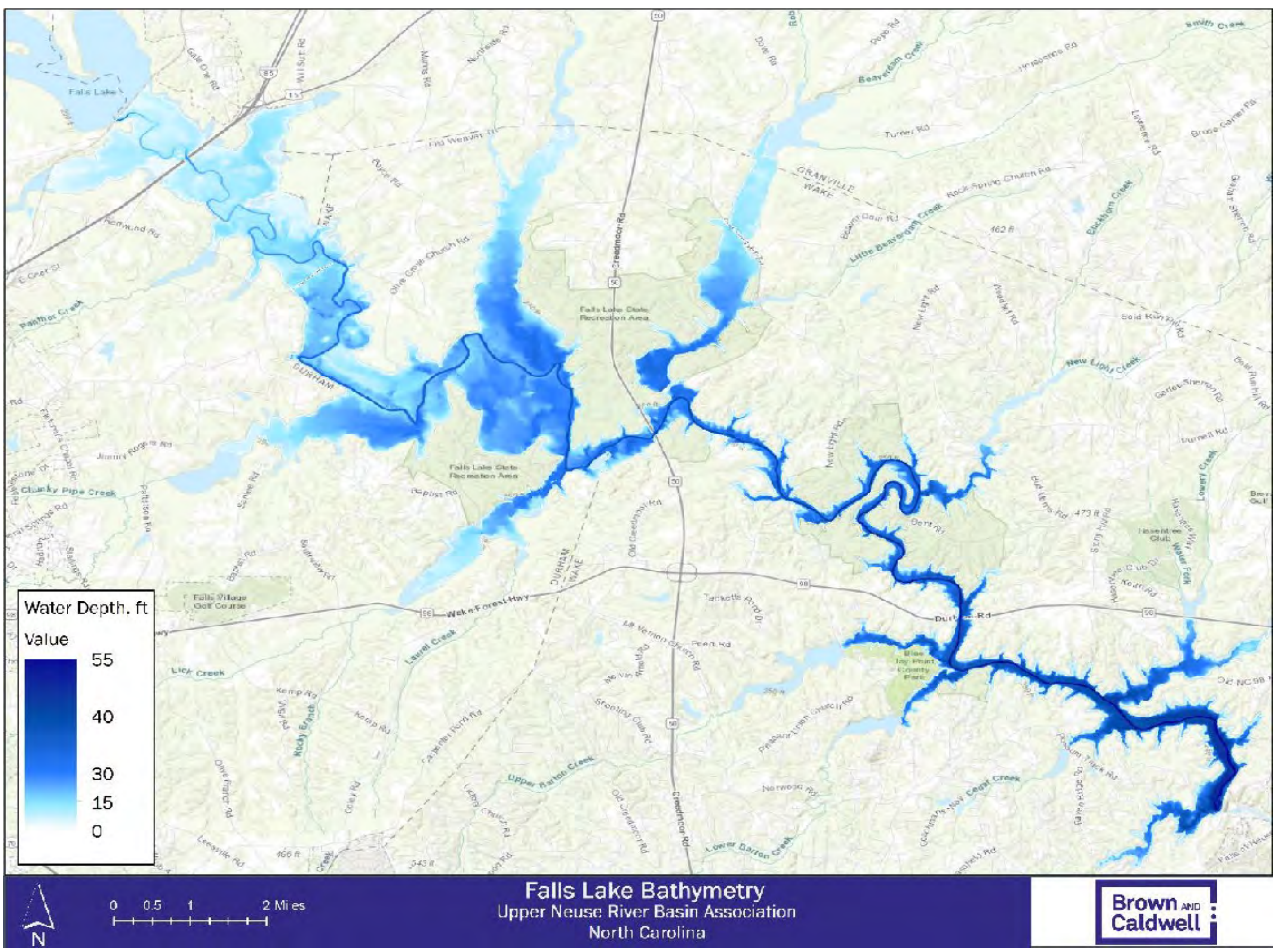
- What are the primary along-lake circulation pattern(s) and physical structures in Falls Lake over times scales from hourly to seasonal?

- How does along-lake circulation vary as functions of:
  - Inflows / Outflows, Meteorology, Physical Properties and Seasons

- What are the primary circulation patterns(s) and physical structures in the large side arms downstream of Fish Dam / Cheek Rd (i.e., Little Lick Creek, Ledge Creek and Lick Creek?

- How and how significantly do these side arms interact with the flow along the main stem?

Falls Lake Bathymetry, data collected 2017, (UNRBA 2019).

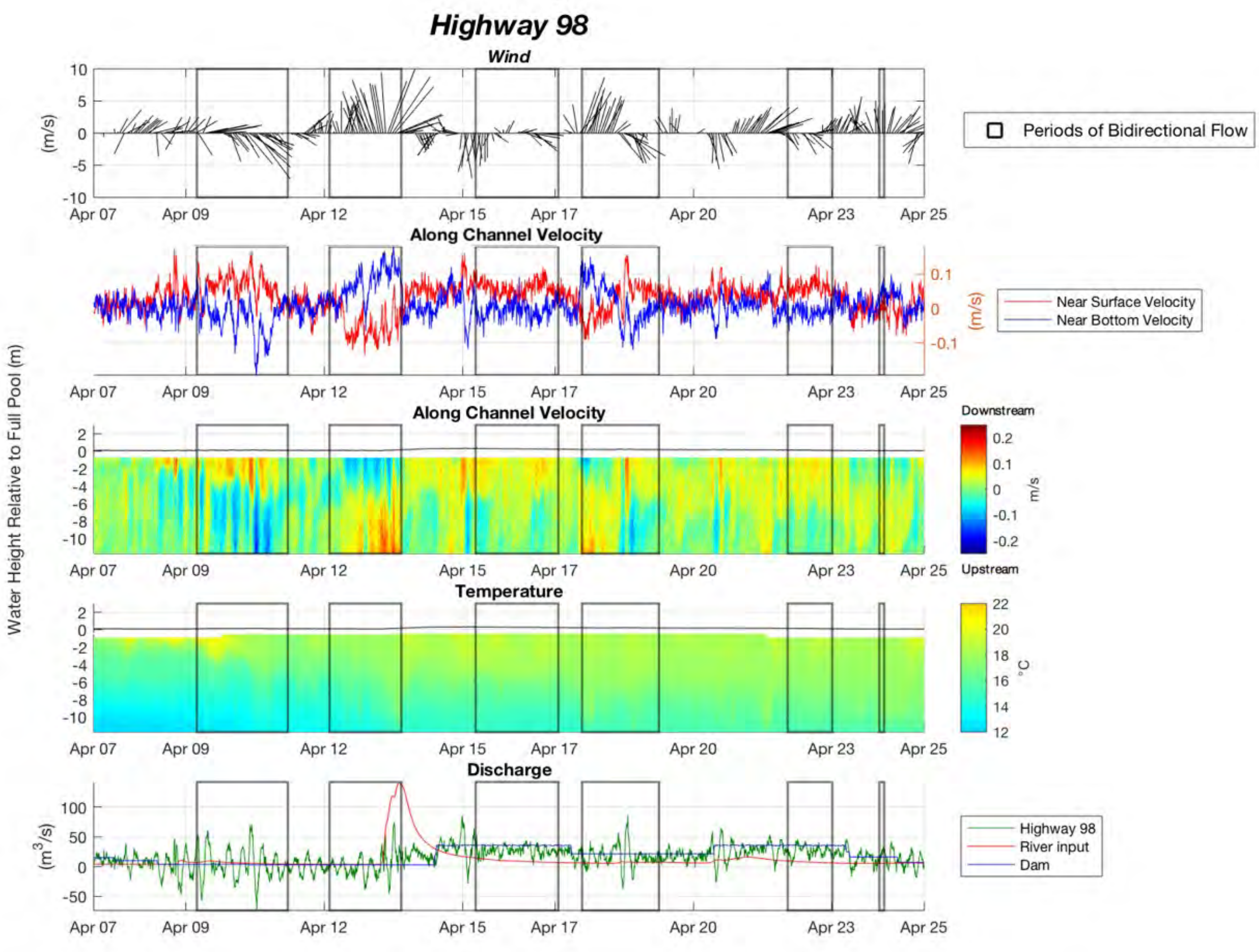


• How does side arm circulation, structure and exchange with the main stem depend on:

- Inflows / Outflows, Physical Properties, Meteorology, and Seasons

• Can a comprehensive in situ data set be collected for use in validating the circulation and physical structure represented in water quality models (e.g., ongoing under the sponsorship of the UNRBA), thereby providing additional confidence in the modeling.

The full In Situ Observation of Falls Lake: Circulation and Physical Characteristics can be found at: https://nutrients.web.unc.edu



An example of wind-driven bi-directional flow at Hwy 98 from April 2020.

From top to bottom: winds, near-surface (red) and near-bottom (blue) along-channel flow speeds, depth-time plot of along-channel velocity, and discharges into the lake (red), at Hwy 98 (green) and over the dam (blue).

Policy in Focus: Evaluating the Benefits of Land Conservation on Water Quality in the Falls Lake Watershed

Falls Lake – a reservoir completed in 1981 by the US Army Corps of Engineers – provides potable drinking water to over half a million people in North Carolina's Piedmont region, serving residents of Raleigh, Garner, Knightdale, Roseville, Wake Forest, Wendell, and Zebulon. Shortly after the lake was impounded, algal levels from excess nitrogen and phosphorus exceeded the state water quality standard. In 2008, Falls Lake was officially listed under Section 303(d) of the Federal Clean Water Act because the reservoir supported chlorophyll-a levels beyond those deemed permissible by the state.

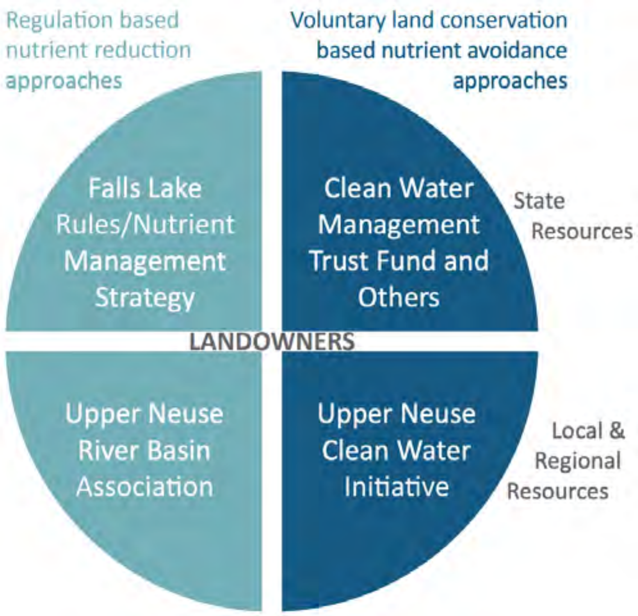
To target excess nutrient inputs, the Falls Lake Nutrient Management Strategy was adopted under the Falls Lake Rules. The Rules address nutrient loading from point and nonpoint sources under three main guiding principles: to return the current nutrient levels back to the 2006 baseline, to protect the lake's use as a drinking water source, and to maintain and enhance current practices by local governments that ensure water quality (15A NCAC 2B .0275). In 2016, the NC General Assembly tasked UNC-Chapel Hill and the NC Collaboratory with analyzing water quality and nutrient management strategies for Falls Lake.

Land conservation and its contribution to nutrient load reductions is one facet of watershed management that the NC Collaboratory is investigating. Research shows that when forest cover drops below 70%, there are measurable negative impacts on a watershed's water quality. Recognizing that approximately 60% of land in Falls Lake is forested, promoting land conservation and maintaining forested areas near waterways can provide numerous benefits to the watershed. Forests store, cycle, and slowly release nutrients like nitrogen and phosphorus to sustain aquatic and terrestrial life.

The presence of conserved land near water bodies reduces flooding, improves animal migration routes, sequesters carbon, reduces streambank erosion, and minimizes algal growth by shading streams. Most relevant to Falls Lake, land conservation can be instrumental in reducing nutrient loading and eutrophica-

George and Julia Brumley Family Nature Preserve, protecting 673 acres of land adjacent to rivers flowing into Falls Lake (photo courtesy of Triangle Land Conservancy).

tion in watersheds through direct and indirect means. Forested land surrounding watersheds acts as a filter for runoff, protects land that would otherwise be developed, serves as a risk management strategy, and ensures that ecosystem services are maintained.



Land conservation programs within the Upper Neuse watershed (graphic courtesy of UNCWI).

Land conservation is a critical component of the Interim Alternative Implementation Approach (IAIA), an optional, investment-based approach for jurisdictions to comply with the Stage I Existing Development Rule. The IAIA follows in the footsteps of the successful Upper Neuse Clean Water Initiative (UNCWI). The Initiative is a program voluntarily funded by a variety of jurisdictions and organizations under the guiding philosophy that protecting this land is the most proactive, holistic, and cost effective way to ensure water quality.

Outside of North Carolina, other watersheds such as the Chesapeake Bay have incorporated land conservation into their management practices, which provide meaningful lessons and potentially new opportunities for land conservation efforts in Falls Lake.

This Policy in Focus piece is a summary of research conducted by Noe Meiri and Adriana Kirk with the UNC Institute for the Environment.

The full Evaluating the Benefits of Land Conservation report can be found at: https://nutrients.web.unc.edu/

Nitrogen Processing in an Urban Reservoir

RESEARCH QUESTIONS

How can we quantify the sedimentary nitrogen processes in order to integrate them into a nitrogen budget for the Falls Lake Reservoir?

RESEARCH METHODS

Water quality degradation due to recurrent algal blooms and eutrophication is common in reservoir systems. Falls lake is a manmade reservoir that has been considered "eutrophic" since 1992 by the NC Department of Environment and Natural Resources (DENR). In order to track sedimentary nitrogen processes in the lake, sediment cores were collected in triplicate along a transect of six sites in the main stem of Falls Lake on 10/14/2019, 5/19/2020, and 8/25/2020, as well as from six Falls Lake tributaries on 7/19/2021.

Ambient water quality data were collected using a SONDE, with surface measurements including temperature, chlorophyll-a, and dissolved oxygen. Following sample collection, sediment cores and water were transported to the Institute of Marine Sciences in Morehead City, to conduct flux assays for various nutrients. Experimental measurements of total nitrogen fluxes were used to calculate annual lake-wide loads from to the Falls Lake reservoir from the sediments.

FINDINGS

- Denitrification rates varied significantly across the selected reservoir tributaries. In general, the least developed catchments were associated with higher capacities to remove nitrogen.

- Spatiotemporal variations in nitrogen processing are linked to changes in temperature and oxygen levels across a longitudinal transect and throughout the water column.

- On an annual scale, nitrogen removal by the sediments only accounts for approximately ¼ of the total nitrogen inputs from atmospheric deposition, tributary runoff, and fluxes from the sediments.

- Reservoir sediments exhibit the capability to permanently remove nitrogen from the system through denitrification. However, removal does not always offset the inputs from the atmosphere, the tributaries, and the sediments, which account for roughly 26% of annual inputs.

MANAGEMENT IMPLICATIONS

- Exclusion of sedimentary processes results in a substantial underestimation of nitrogen inputs to reservoirs.

- Policies aimed at reducing anthropogenic nitrogen inputs could mitigate water quality degradation to some extent, but will likely not prevent algal blooms completely.

- Excess nitrogen may be a characteristic of urban reservoir systems, and water quality standards should reflect that.

RESEARCHERS

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Background

Reservoirs are man made aquatic environments, created when a dam is constructed on a river. They are constructed for flood control purposes, to provide drinking water, and for hydropower. Population growth and the associated need for these functions can explain marked global increases in dam construction. There are tradeoffs between societal benefits and ecological impacts. Interrupted flow regimes can influence physical, biological, and chemical properties of natural systems, and can disrupt beneficial ecological functions, such as water quality regulation.

Reservoirs are unique aquatic ecosystems. As hybrid systems, they combine characteristics of riverine and lacustrine environments and exhibit distinct zones characterized primarily by flow velocity and geomorphology. The riverine zone is the furthest upstream, characterized by relatively high horizontal flow velocity. In the transition zone, flow velocities decrease and depths increase. The lacustrine zone is furthest downstream closest to the dam. This region is most similar to large lake systems, with low flow velocities and relatively high residence times.

Distinct hydrodynamic characteristics influence physical conditions across a longitudinal transect (e.g., high turbidity in the riverine zone that decreases downstream) and throughout the water column (e.g., more pronounced vertical temperature and oxygen gradients in the lacustrine zone) affect biological processing and availability of nutrients.

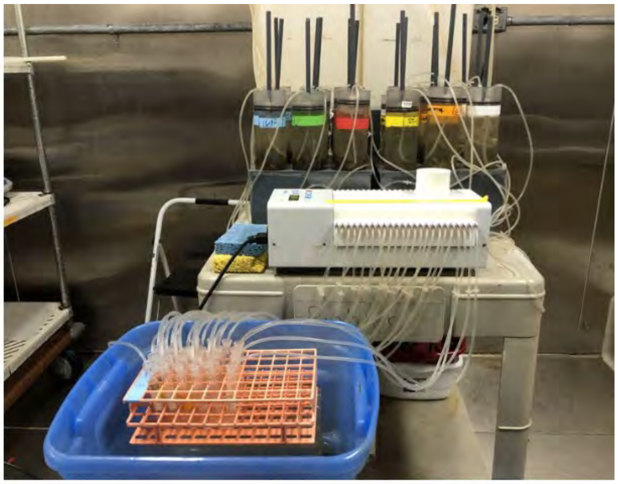
Water quality degradation due to recurrent algal blooms and eutrophication is common in reservoir systems. This could be explained by longer residence times that promote primary productivity, especially in the lacustrine zone. Excess nutrients can also stimulate algal blooms. Anthropogenic sources of nitrogen have increased substantially in the last century, accelerating water quality degradation. Nitrogen point sources, such as waste water treatment facilities, directly discharge nitrogen containing effluent into waterbodies. Non-point source nitrogen from agricultural and urban landscapes enters waterways via stormwater runoff.

This increased anthropogenic nitrogen load and subsequent algal blooms have prompted policies on multiple political levels. The Clean Water Act (1972) is a federal policy that requires states to conduct water quality assessments of navigable waterways and listing those considered "impaired". An impairment classification warrants the state to develop management strategies to reestablish acceptable water quality. Common strategies employed by states include total maximum daily loads (TMDLs) to target point source pollution and habitat conservation and restoration efforts to target non-point source pollution.

In addition to limiting development and associated anthropogenic pollutants, habitat conservation and restoration measures (e.g., vegetative buffer protection programs) utilize the natural processes by which habitats regulate water quality. Floodplain forests and wetlands are able to intercept nutrients transported via stormwater and permanently remove bioavailable forms of nitrogen through denitrification (DNF;. DNF is an anaerobic microbially mediated process that converts reactive nitrogen to dinitrogen gas (N_2), which is permanently lost to the atmosphere. DNF by coastal habitats has been established as a valuable ecosystem function; however, less is known about DNF in reservoir sediments, which influences nitrogen concentrations and delivery once it enters the reservoir.

Even with management efforts, recurrent algal blooms are common. It is possible that reservoir sediments act as an internal source of reactive nitrogen. Processes, such as nitrogen fixa-

Collecting and sampling sediment cores.



tion, organic matter remineralization, and dissimilatory nitrogen reduction to ammonium (DNRA), add reactive forms of nitrogen to aquatic systems, and are poorly understood in reservoirs. Legacy nutrients may also contribute to nitrogen flux. These are nutrients that are stored in the sediments or groundwater that re-enter the system on a timescale of years to centuries. If efflux of reactive nitrogen exceeds removal via DNF, reducing anthropogenic nitrogen inputs would not necessarily achieve water quality standards. Thus, understanding this piece of the reservoir nitrogen budget is critical.

Despite their prevalence, little is known about nitrogen processing in reservoir systems. The overall objective of this study is to quantify nitrogen processing in the sediments of an urban reservoir. Specifically, this work assesses seasonal environmental variables that affect nitrogen production and removal in the main stem of the Falls Lake reservoir, NC, USA. Additionally, this research investigates the influence of land use in surrounding catchments on nitrogen processing in Falls Lake tributaries. Understanding the internal sources, sinks, and processes that regulate the availability and distribution of reactive nitrogen in urban reservoirs will inform nutrient budget models and water quality policy regarding these manmade aquatic environments.

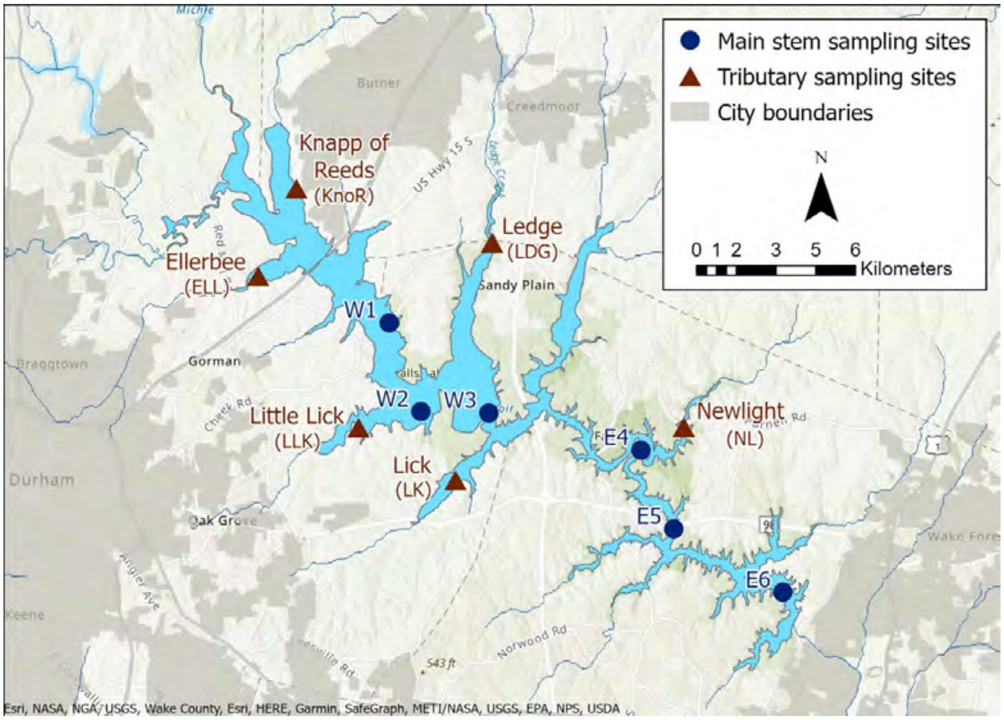
Seasonal Nitrogen Processing in Main Stem of Reservoir

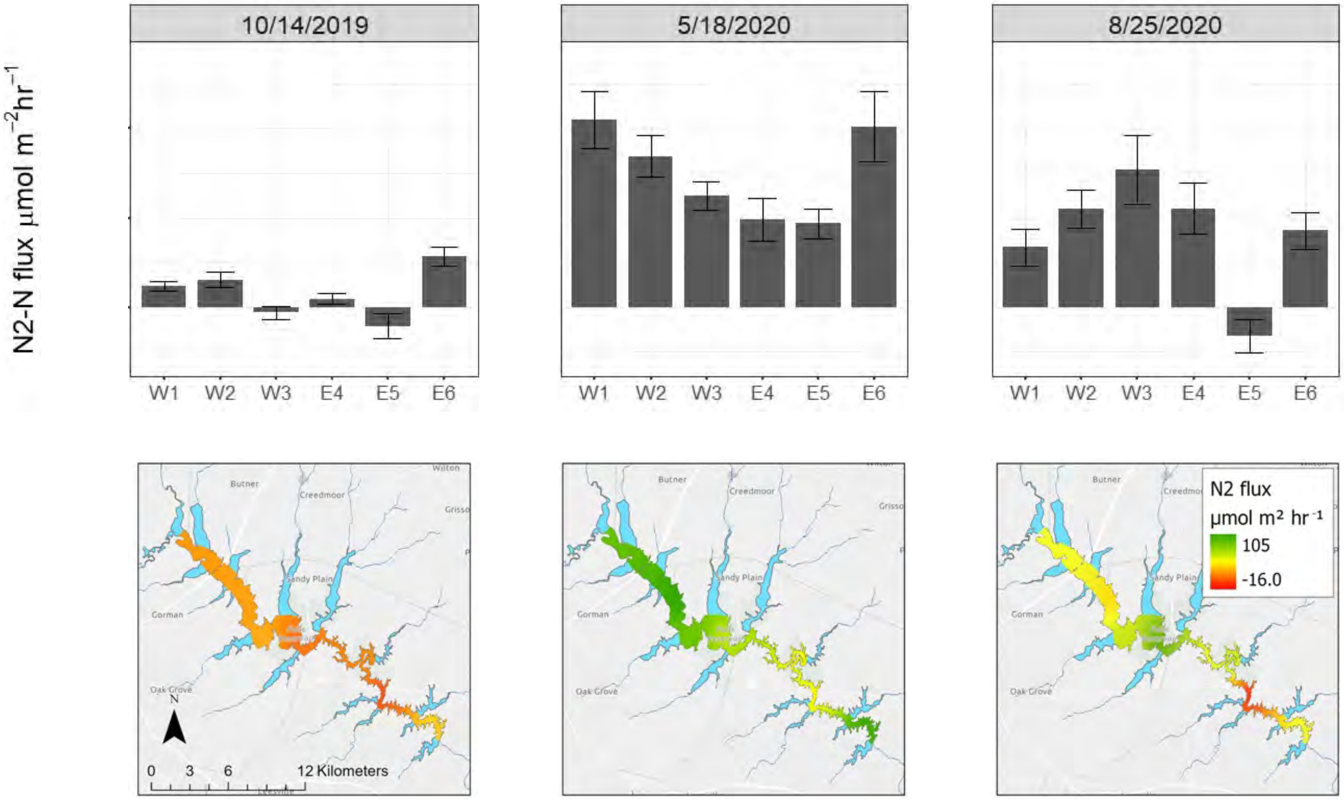
Nitrogen fluxes were variable across main stem sites and between sampling dates. In October, N_2-N fluxes ranged from 28.5 ± 5.06 to -10.6 ± 21.0 µmol m^2 h^(-1). The highest rates were observed at E6, which were significantly higher than rates at the other five sites. Negative N_2-N fluxes indicate nitrogen fixation, or addition of DIN to the system. Nitrogen fixation occurred in W3 and E5 sediment cores, producing rates that were significantly lower than W1, W2, and E6. In May, net DNF occurred at all sites, with N_2-N fluxes ranging between 46.9 ± 8.32 to 105 ± 15.8 µmol m^2 h^(-1). The lowest rates were measured in E4 and E5 cores, which were significantly lower than rates measured W1, W2, and E6 cores. Mean fluxes at W1, W2, W3, and E6 were comparable. In August, net DNF was observed at all sites except E5. Mean N_2-N fluxes ranged from -16.1 ± 9.44 at E5 to 76.9 ± 57.1 at W3. Rates at E5 were significantly lower than other sites. DNF at other sites were comparable, expect that W1 produced significantly lower rates than W3.

NO_x fluxes were less variable across the Falls Lake main stem than N_2-N. In October, NO_x fluxes were positive, indicating the sediments acted as a NO_x source. Recorded rates were as low as 0.140 ± 0.140 µmol m^2 h^(-1) at E5 and as high as 24.1 ± 12.4 µmol m^2 h^(-1) at W2, but there was no statistically significant spatial variation between fluxes. Similarly, in May, main stem sediments acted as a NO_x source and there was no evident spatial variation in NO_x fluxes. The lowest rate measured was 0.175 ± 1.29 µmol m^2 h^(-1) at E5 and the highest was 6.20 ± 3.54 µmol m^2 h^(-1) at W2. Some spatial variation in NO_x

Sampling map of Falls Lake.

Sediment cores and water samples were collected from the main stem of the reservoir 10/14/2019, 5/18/2020, and 8/25/2020. Cores and water also were collected from tributary reservoirs on 7/19/2021.





Mean N2-N fluxes (top) and spatial interpolation of mean N2-N fluxes (bottom) across Falls Lake main stem sites in October, May, and August. Service layer credits: Esri, Here, Garmin, SafeGraph, METI/NASA, USGS, EPA, NPA, USDA.

Conclusions

This study aimed to quantify sedimentary nitrogen processes and integrate them into a nitrogen budget for the Falls Lake Reservoir. Results revealed that spatiotemporal variations in nitrogen processing are linked to changes in physiochemical conditions across a longitudinal transect and throughout the water column. These characteristics coincide with distinct zones in a reservoir determined by geomorphology and hydrology. Reservoir sediments exhibit the capability to permanently remove nitrogen from the system through DNF. However, removal does not always offset the input of DIN from the sediments.

Development at the watershed scale likely influences nitrogen processing, resulting in a reduced capacity to remove nitrogen via DNF and increased capacity to act as a source of DIN. More work needs to be done to understand the differences in lability of urban and natural sources of nitrogen and the effects on removal capacity. Additionally, more needs to be done to understand environmental conditions that trigger the release of DIN from tributary sediments into the water column.

On an annual scale nitrogen removal by the sediments only accounts for approximately one quarter of the TN inputs from atmospheric deposition, tributary runoff, and fluxes from the sediments. Therefore, policies aimed at reducing anthropogenic nitrogen inputs could mitigate water quality degradation to some extent but will likely not prevent algal blooms completely. Furthermore, excess nitrogen may be a characteristic of urban reservoir systems, and water quality standards should reflect that. Reservoirs have become an important part of developed landscapes, providing drinking water and recreational opportunities. Demand for their functions will increase with population growth, and understanding processes that may degrade environmental quality and inhibit these functions is critical.

The full Nutrient Processing in an Urban Reservoir report can be found at: https://nutrients.web.unc.edu/

Assessment of Zooplankton-Phytoplankton Relationships

RESEARCH QUESTIONS

1) Does the spatial/temporal distribution of zooplankton and phytoplankton within Falls Lake indicate strong or weak trophic transfer between phytoplankton and zooplankton production?

2) How does the trophic transfer efficiency in Falls Lake compare to other southeastern US reservoirs?

3) Is there a clear inflection point in the slope of the relationship between zooplankton and phytoplankton biomass for Falls Lake that may guide development of a site-specific criterion?

4) Is there a clear inflection point in the slope of the relationship between zooplankton and phytoplankton biomass for southeastern reservoirs that may help guide development of a region-specific criterion for phytoplankton biomass that could be adopted for use in Falls Lake?

RESEARCH METHODS

From 2009 to 2012, zooplankton samples were collected monthly at ten monitoring stations by Sandra Cooke (UNC Greensboro) along with concurrent measurements of photic zone Chl a concentration made by NC State's Center for Applied Aquatic Ecology. Zooplankton samples were collected at ten CAAE monitoring stations with approximate monthly frequency from 2009 to 2012. The stations were grouped into three clusters within the upper main arm of the lake, a mid-lake region near the HWY 50 bridge and a lower lake region from HWY 98 to the dam. From each station, duplicate zooplankton samples were collected using a vertical net tow from the bottom to the surface and a concurrent depth integrated photic zone measurement of Chl a. Biomass of each zooplankton taxa within each sample was calculated by multiplying measured organism density by estimates of the dry body weights for each taxa. Total zooplankton biomass at each site visit was calculated as the sum of the biomass of all taxa observed.

FINDINGS

Though the composition of zooplankton in Falls Lake was similar to other southeastern reservoirs, median summer biomass and abundance of zooplankton in Falls Lake were less than a third of those reservoirs. Comparatively low zooplankton biomass cannot be explained by lack of fertility because median phytoplankton biomass of Falls Lake quantified by Chl a was nearly three-fold higher than the other reservoirs. Zooplankton biomass: Chl a ratios averaged nearly an order of magnitude lower for Falls Lake than the other reservoirs. This indication of poor trophic transfer efficiency was contradicted by seasonal patterns of zooplankton and Chl a that indicated strong trophic coupling during a burst of spring zooplankton production and a positive relationship between zooplankton and Chl a along the upstream to downstream trophic gradient in the reservoir. The generally low zooplankton: Chl a ratio in Falls Lake is likely due in part to intense predation on zooplankton by planktivorous larval fish. There was no inflection point in the zooplankton: Chl a relationship for Falls Lake and only weak evidence for an inflection point in data from southeast reservoirs.

MANAGEMENT IMPLICATIONS

Examination of the zooplankton and phytoplankton relationships in Falls Lake produced contradicting evidence regarding the strength of trophic coupling. Annual average zooplankton: Chl a values indicated poor trophic coupling but closer examination of the seasonal and spatial patterns suggested that phytoplankton production was significantly linked to zooplankton production. A region-specific Chl a criteria of 51 mg L-1 was weakly supported by using the US EPA's NLA dataset for southeastern U.S. reservoirs to identifying an inflection point in a hump-shaped empirical model that related zooplankton biomass and Chl a. Due to the weak fit of the model for region-wide data and lack of an observed inflection point within the Falls Lake zooplankton: Chl a data, it is currently unadvisable to pursue setting a site-specific Chl a standard for Falls Lake based on zooplankton: Chl a relationships.

RESEARCHERS

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Background

This project examines the trophic relationship between zooplankton and phytoplankton within Falls Lake, North Carolina to provide guidance for development of site-specific numeric nutrient criteria protective of aquatic life uses. Nutrient enrichment of lakes and reservoirs generally stimulates productivity throughout the food web. However, the degree of stimulation of higher trophic levels is often less than at the level of primary producers. Changes in the palatability and nutritional value of primary producers and structural changes to the food web occur as nutrient enrichment progresses that tend to decrease the efficiency of trophic transfer from primary producers to zooplankton.

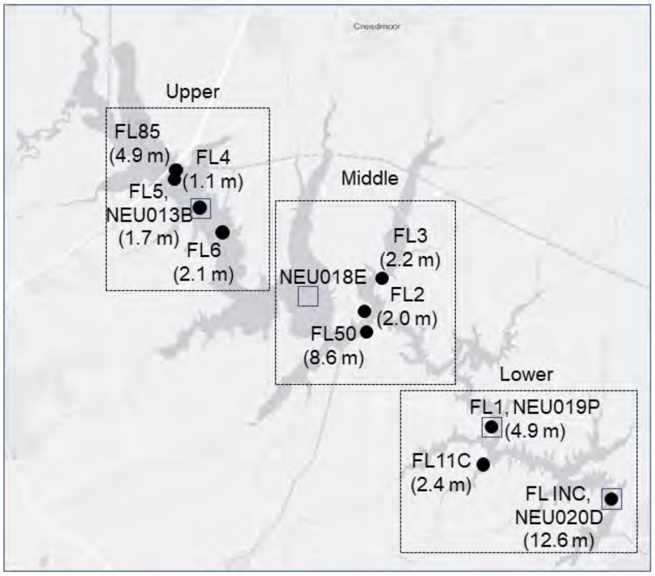
The decreased transfer efficiency of organic matter causes many of the classic symptoms of eutrophication including accumulation of excess phytoplankton in the photic zone with shading of benthic autotrophs, and sedimentation into the hypolimnion leading to hypoxic bottom waters.

The important role that the efficiency of trophic transfer plays in determining the expression of eutrophication has generated significant interest in using trophic transfer efficiency as a metric for establishing regulatory criterion for acceptable levels of phytoplankton biomass in U.S. lakes and reservoirs. Rates of primary and secondary production required to calculate trophic transfer efficiency are rarely measured, but the ratio of the biomass of zooplankton to phytoplankton can be a useful proxy for changes in transfer efficiency that result from nutrient enrichment. An analysis of summertime zooplankton: phytoplankton biomass ratios for deep (>8 m depth) lakes throughout the United States revealed an inflection point in the slope of the relationship between zooplankton and phytoplankton biomass which has been interpreted as threshold level of phytoplankton biomass where coupling of zooplankton and phytoplankton production begins to deteriorate.The inflection point analysis has been proposed as a way to quantify phytoplankton biomass criterion that are protective of aquatic life uses for U.S. lakes and reservoirs.

Besides the level of nutrient enrichment, trophic transfer efficiency is also strongly affected by climatic conditions, hydrology, morphometry, fish community structure, and water chemistry. These factors that are largely system-specific result in wide variation in trophic transfer efficiency for a given level of nutrient enrichment, and indicate that a single level of trophic transfer efficiency may not be appropriate for establishing acceptable levels of phytoplankton biomass across the thousands of disparate lakes and reservoirs in the United States. More effective criterion for phytoplankton biomass levels may be developed by considering site specific information on trophic transfer efficiency.

Since the 1970's, North Carolina's water quality standard for phytoplankton biomass has been based on chlorophyll a (Chl a) concentration and set as a do not exceed value of 40 g L-1 for all surface waters except mountain trout streams. The level of this standard (40 g L-1) was based largely on best professional judgement with considerations for water clarity and a desire to prevent negative consequences from harmful algal blooms and to protect aquatic life (NCDP SAC 2020). Although the standard has been in place for more than 40 years, the validity of the standard for protection of aquatic life in NC surface waters has rarely been assessed. Many of NC's reservoirs, including Falls Lake, have consistently violated the standard since their creation despite having productive fisheries and heavy recreational use that indicate that violation of the Chl a standard may not be strongly linked to impairment of aquatic life and recreational use in these impoundments (NCDP SAC 2020).

Water quality in Falls Lake is currently managed under the Falls Reservoir Nutrient Management Strategy which has established a plan for meeting the current water quality standards throughout all of Falls Lake by reducing N and P loads by 40 and 77 %, respectively, by the year 2040 at a cost of approximately 1 billion dollars (UNRBA 2019; Stage II of the Falls Reservoir Nutrient Management Strategy). Given the high cost of the nutrient reduction efforts, it is important to use best scientific evidence to establish the linkage between phytoplankton biomass measured as Chl a



Map of zooplankton sampling stations (filled circles), average net tow depths at those station (in parentheses), and NC DEQ stations where phytoplankton community composition is monitored in Falls Lake (open squares).

and designated uses in Falls Lake. This project specifically seeks to understand the relationship between phytoplankton biomass as measured by Chl a and support for aquatic life as indicated by zooplankton biomass.

This study examines a three year (2009-2012), approximately monthly record of zooplankton and phytoplankton biomass at 10 sites throughout Falls Lake and compares the plankton of Falls Lake to other southeastern United States reservoirs to address the following questions.

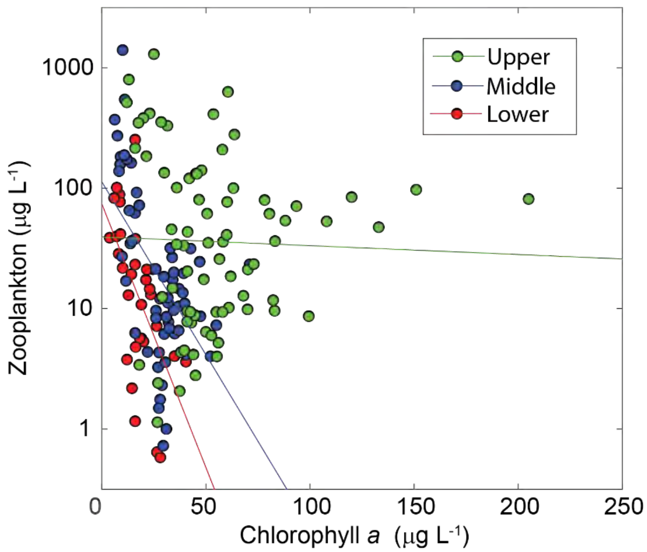
1) Does the spatial/temporal distribution of zooplankton and phytoplankton within Falls Lake indicate significant coupling or decoupling between phytoplankton and zooplankton production?

2) How does the trophic transfer efficiency in Falls Lake compare to similar water bodies in the southeastern US?

3) Is there a clear inflection point in the slope of the relationship between zooplankton and phytoplankton biomass for Falls Lake that may guide development of a site-specific criterion?

4) Is there a clear inflection point in the slope of the relationship between zooplankton and phytoplankton biomass for southeastern reservoirs that may help guide development of a region-specific criterion for phytoplankton biomass that could be adopted for use in Falls Lake?

biomass of Falls Lake quantified by Chl a was nearly three-fold higher than the other reservoirs. The combination of low zooplankton biomass and high Chl a led to Z:Chl a ratios that averaged nearly an order of magnitude lower for Falls Lake than the other reservoirs. This indication of poor trophic transfer efficiency in Falls Lake was examined further by assessing correlations between zooplankton and phytoplankton biomass over space and time in Falls Lake.



Log linear scatter plot of concurrent measurements of crustacean zooplankton biomass and chlorophyll a in the Upper, Middle and Lower regions of Falls Lake.

Results and Discussion

Twenty-five taxonomic categories of zooplankton were identified by Dr. Cooke from the Falls Lake samples. Biomass and abundance of crustacean zooplankton were dominated by copepods and cladocerans with other crustaceans, predominantly ostracods, constituting less than 1%. Seasonally, copepods were dominant in the warm months from May to September but cladocerans dominated biomass during the cooler months from October through April. At this level of taxonomic resolution, the warm season zooplankton community of Falls Lake appears typical of other southeastern U.S. reservoirs with biomass and abundance dominated by copepods, cladocerans forming about a third of biomass, and other crustaceans constituting a small fraction.

Though the composition of zooplankton in Falls Lake was similar to other southeastern reservoirs, median summer biomass and abundance of zooplankton in Falls Lake was less than a third of those reservoirs. Comparatively low zooplankton biomass cannot be explained by lack of fertility because median phytoplankton

Key Takeaways

1) Compared to other southeastern reservoirs the average zooplankton to phytoplankton biomass ratio of Falls Lake is indicative of a poor efficiency of trophic transfer from phytoplankton to zooplankton.

2) In contrast to conclusion 1, a burst of zooplankton production that terminates the spring phytoplankton bloom and a positive correlation of zooplankton biomass with Chl a along the downstream trophic gradient provide evidence for a strong trophic linkage between Chl a and zooplankton biomass in Falls Lake.

3) Strong and opposite seasonal patterns of zooplankton and phytoplankton likely resulted from zooplankton consumption of phytoplankton in spring and fish consumption of zooplankton during summer. The resultant, negative relationship precluded identification of an inflection point in the zooplankton: phytoplankton relationship that could be used to develop a lake-specific Chl a criteria.

4) A region-specific Chl a criteria of 51 g L-1 was derived using the US EPA's NLA dataset for southeastern U.S. reservoirs by identifying an inflection point in a hump-shaped empirical model that related zooplankton biomass and Chl a. This criteria value is consistent with criteria determined by the US EPA (2021) for shallow reservoirs similar to those of the southeastern U.S. However, the hump-shaped empirical model fit the data only slightly better than a positive linear model which casts doubt on the underlying assumption of a hump-shaped relationship and thus, the validity of the derived Chl a criteria.

Management Implications

Based on the lack of strong evidence for a hump-shaped relationship between zooplankton and phytoplankton biomass for southeastern reservoirs, it is currently unadvisable to pursue setting a site specific Chl a standard for Falls Lake based on zooplankton: Chl a relationships.

The full Assessment of Zooplankton-Phytoplankton Relationships report can be found at: *https://nutrients.web.unc.edu/*

Policy in Focus: Can Amending the Falls Lake Rules Result in Achieving the Nutrient Water Quality Standards?

North Carolina has a significant number of water supply sources that are not attaining the Water Quality Standards ('WQS") for nutrient control. The three primary stages of the WQS process are: (1) monitoring to establish the extent of the nutrient loading; (2) modeling to establish a budget to achieve the WQS adversely impacted, including chlorophyll-a; and (3) adopting rules to implement the program. Twenty lakes and reservoirs listed in the most recent biennial report to the U.S. Environmental Protection Agency ("EPA") have none of these nutrient control strategies in place. Several of the water bodies are the primary drinking water supply for metropolitan areas where growth is rampant. The challenges are not only financial but may also include the substantial staff and programmatic shortfalls in the Department of Environmental Quality ("DEQ").

Each step of the regulatory scheme to address the amount of nutrient loading involves considerable time demands for DEQ staff. Establishing the allowable nutrient load to attain compliance with the WQSS requires several years of monitoring and modeling in advance of the rulemaking for each waterbody. These activities are performed by the Division of Water Resources ("DWR") and adopted by the Environmental Management Commission ("EMC"). The EMC has adopted the loading budget and implemented rules for only six of the listed water supply sources. As such, an immediate need is the development of the loading allocation and regulatory programs for the additional water supplies on the list.

Recently, DWR cited a provision of the federal Clean Water Act in defending its refusal to issue speculative limits for a proposed new wastewater treatment plant because it would discharge into the Yadkin River, a tributary to High Rock Lake. DWR contended that the proposed project is blocked by 40 CFR §122.4. If that policy is applied to all §303(d) waters listed for failure to attain nutrient water quality standards ("WQS") for which there is no nutrient budget and supporting allocations, substantial adverse impacts will result to the environment and to the economy of the State.

The Falls Lake rules were adopted in 2011 to establish the load reductions necessary to demonstrate compliance with the chlorophyll-a WQS.

Based on the scientific examination of Falls Lake by the Collaboratory and the Upper Neuse River Basin Association ("UNRBA"), it is clear that compliance with current nutrient WQS cannot be achieved in a timely manner.

DWR has approved both watershed and long-term plans to address pollutants including nutrients. One such plan extends over 30 years. Additionally, collaboration between the regulated entities and states to ease burdens on the state agency with the long-term implementation of nutrient strategies are discussed. Other states with Piedmont impoundments have seldom met with complete success in the control of excess nutrients; however, several states have pursued solutions or policy methods that provide long-term strategies without threatening litigation to enforce multiple regulatory requirements.

Likewise, EPA has entered into Consent Decrees based on a long-term strategy for the enhancement and restoration of watersheds, including nutrient reductions. The current statutory framework for collaboration can be expanded which will allow the Department of Environmental Quality to focus on other waterbodies with unaddressed nutrient problems. The existing legislative framework for addressing nutrient-impacted water bodies provides an alternative that can allow the development of long-term plans reliant on the most likely resource to address the problem—local governments, with State oversight to meet the Clean Water Act requirements for a delegated program. Thus far, this strategy has not been employed.

The more recent realization that nutrient management strategies will require high-cost, long-term solutions create a need to allow longer planning and financing systems than the five-year duration of NPDES permits. Local governments within a basin of a waterbody with pollution problems can create a coalition to present a Water Quality Protection Plan to the EMC. The Water Quality Management Plan is authorized under federal and state law "as an alternative method of attaining water quality standards in a basin."

To qualify as a local government coalition eligible to present a plan, the plan must be presented "through a nonprofit corporation" incorporated with the Secretary of State with sufficient territorial area in the basin to achieve the water quality restoration. The plan must be approved by the governing body of each coalition member and "provide a viable alternative method of attaining equivalent compliance with federal and State water quality standards, classifications, and management practices in the affected basin." With EMC approval, coalition members are allowed to "establish and implement a pollutant trading program for specific pollutants between and among point source dischargers and nonpoint pollution sources." The Falls Lake rules are not a coalition plan approved under this statute and no such plan has been presented from any basin.

The revision of the EMC/DWR nutrient strategy to include such long-term planning and implementation, as well as local coalitions, is also supported by policies of the U.S. Environmental Protection Agency. This would be a timely and important opportunity for the State, as it addresses the increasing need for implemented nutrient management strategies, to implement a program broad program to address the need for long-term strategies for water quality issues such as those in Falls Lake. The coalition approach also will strengthen the empowerment of the local governments tasked with accomplishing the implementation of the nutrient management strategy while providing them the flexibility to include other issues of water quality in the coming decades.

Substantial research for the re-examination of the Falls Lake rules illustrates the complexity of addressing nutrient overload-enrichments. The reductions achieved during Stage I of the rules have removed from the potential inventory of sources most of the load reductions that can be achieved by 2041. The time for natural processes to address the "legacy" nutrients stored in the sediments in the reservoirs, in streambanks, and in groundwater, pushes the projected date for the achievement of the goals of the nutrient management strategy substantially beyond 2041.

The adaptive management strategy for the next increment of progress on the achievement of an attainment status for Falls Lake for nutrients provides an excellent opportunity for North Carolina to implement a water quality protection plan consistent with the vision set forth by EPA Assistant Administrator for Water Fox in her April 2022 memorandum. The fundamental structure is already in place from N.C. Gen. Stat. § 143-214.14. With modest changes, the statute can be revised to take into account elements of the Georgia legislation and the Integrated Plan framework of the EPA. The chance to promote local government support and to achieve a successful nutrient management plan is through a cooperative voluntary program, instead of by a court-ordered program. This approach can open a new dimension in the clean water programs for North Carolina.

This Policy in Focus: Can Amending the Falls Lake Rules Result in Achieving the Nutrient Water Quality Standards? is a summary of research conducted by Dan McLawhorn, a legal and policy consultant for the Falls Lake study. The full report can be found at https://nutrients.web.unc.edu/

Defining the Balance Between Cyanobacterial Fixation and Denitrification

RESEARCH QUESTIONS

1) Do microbial processes cause a net production (N_2 fixation) or removal (denitrification) of biologically available N from Falls Lake?

2) Is N_2 fixation quantitatively important relative to stream loads and atmospheric deposition, and therefore, worth including in water quality models?

3) What factors stimulate or constrain N_2 fixation in Falls Lake?

RESEARCH METHODS

Rates of microbial N_2 fixation were measured from spring through fall during 2019 to 2022 at six main channel and ten creek arm stations using the acetylene reduction technique. Concentrations of bioavailable N and P, light availability, physical conditions, and the biomass and composition of the phytoplankton community were also measured to understand factors that relate to N_2 fixation. Measured rates were scaled up to annual lake-wide estimates. The measured rates were also compared to the biomass of heterocystous cyanobacteria during each measurement to produce a biomass-specific N_2 fixation rate. The biomass-specific rate was used to estimate a time series of N_2 fixation based on historical records of heterocystous cyanobacteria biomass measured by the NC Dept. of Environmental Quality (NCDEQ).

FINDINGS

Direct measurements and biomass-based estimates of N_2 fixation indicated that N_2 fixation contributes less than 1% and about 6% of total N inputs to Falls Lake, respectively. Such a small fraction of total N inputs justifies omitting the process in eutrophication models for Falls Lake. Based on the mass balance and direct core measurements of denitrification it appears that denitrification exceeds N_2 fixation and that the balance of these microbial processes result in a net loss of N from Falls Lake. Net loss of N could help maintain N limited phytoplankton which is consistent with N limited growth observed in nutrient addition experiments conducted in spring and summer 2021. Most of the N and P within Falls Lake are bound up in plankton biomass. P is not available in great excess and appeared to be an important constraint on N2 fixation.

MANAGEMENT IMPLICATIONS

This situation of N limitation but with the potential for stimulation of N_2 fixation by P suggests that dual management of N and P is warranted for preventing undesirable levels of phytoplankton biomass in Falls Lake.

RESEARCHERS

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Introduction

The balance between N_2 fixation by cyanobacteria and N removal via denitrification is a critical driver of phytoplankton nutrient limitation in lakes and reservoirs. Denitrification in shallow, highly productive lakes and reservoirs can remove significant quantities of N that in combination with efficient trapping of P can lead to strong N limitation. N limitation has the potential to favor cyanobacteria groups capable of N_2 fixation. Examination of DWR's phytoplankton community composition data indicated that heterocystous cyanobacteria capable of N_2 fixation regularly comprise 25% or more of the phytoplankton biomass during the summer, but water quality models for Falls Lake including NCDEQ's model and current modeling efforts by the Upper Neuse River Basin Association (UNRBA) do not contain a N_2 fixing cyanobacteria group. Omission of a N_2 fixing cyanobacteria group precludes the ability to simulate these N inputs to the reservoir and could create severe errors in estimation of phytoplankton biomass responses if N_2 fixation is an important process or could become quantitatively important if N inputs are reduced.

Constraining N inputs by N_2 fixation significantly enhances our understanding of phytoplankton nutrient responses in Falls Lake and fills a significant data gap in the N mass balance for Falls Lake. Filling this gap of N inputs to Falls Lake allows calculation of lake-wide N losses via denitrification using a mass balance approach. Denitrification rates calculated by the mass balance complement direct measurements of denitrification made on sediment cores by Dr. Piehler's lab as part of the Collaboratory's Falls Lake Nutrient Study and denitrification estimates produced by a sediment diagenesis model calibrated with sediment porewater concentration data from Falls Lake. Collectively, these efforts provide significant information on water column and sediment N cycling within Falls Lake that will aid understanding responses of Falls Lake water quality to a rapidly changing watershed and climate and will inform future modeling efforts.

Research Questions:

1) Do microbial processes cause a net production (N_2 fixation) or removal (denitrification) of biologically available N from Falls Lake?

2) Is N_2 fixation quantitatively important relative to stream loads and atmospheric deposition, and therefore, worth including in water quality models?

3) What factors stimulate or constrain N_2 fixation in Falls Lake?

Methods

Sampling:

Between July 2019 and August 2022, a series of sampling campaigns were conducted along a transect of 6 main channel stations and at 10 creek arm sites to measure N_2 fixation and the biological, physical, and chemical characteristics at each site.

Measurement of water column N2 fixation:

All N2 fixation measurements were conducted using the acetylene reduction assay. During fall 2019 and summer 2020, N_2 fixation measurements conducted at mid-channel locations were made at different light levels to understand how N_2 fixation responded to the strong vertical light gradient in Falls Lake. For creek arm samples collected during 2021 and the creek arm and mid-channel samples collected during summer 2022, N_2 fixation measurements were made at a single irradiance level (20% incident light). For all measurements, water temperature was maintained at the in situ temperature.

Measurement of nutrients, vertical structure of the water column, and phytoplankton biomass and community composition:

Depth profiles of temperature, conductivity, dissolved oxygen, pH, and photosynthetically active radiation (PAR) were measured at each sampling event. The euphotic zone depth was calculated as the depth of 1% PAR penetration.

For each sample, nutrient measurements included dissolved ammonium, nitrate+nitrite, phosphate, total dissolved nitrogen, and silicate, and particulate nitrogen. Phytoplankton biomass was estimated as chlorophyll a and accessory photopigments measured by HPLC were used to estimate the biomass of different phytoplankton classes including cyanobacteria. An aliquot of each sample was additionally preserved in Lugol's solution for species-level microscopic identification and enumeration of the phytoplankton community. Biomass of potentially N_2 fixing, heterocystous cyanobacteria within the order Nostocales were microscopically quantified based on methods in Hall and Paerl (2011).

Relationships between N_2 fixation and bioavailable, inorganic N and P nutrient forms (nitrate, ammonium, and phosphate), and cyanobacteria biomass determined by accessory photopigments and by microscopy were explored using Spearman's rank correlations to improve understanding of the controls on N_2 fixation in

Map of main channel and creek sampling stations for measurements of N fixation rate. Five of the six main channel stations coincided with stations sampled monthly by NC Dept. of Environmental Quality

Falls Lake. Details of data treatment including treatment of censored values are provided in the Supplemental Information.

Examination of the relationship between directly measured rates of N_2 fixation and microscopically determined biomass of heterocystous cyanobacteria biomass allowed an estimate of the biomass-specific rate of N_2 fixation. Comparing our observed biomass-specific N_2 fixation rates against literature values allowed us to assess how active the N_2 fixing cells of Falls Lake are compared to that observed in other systems, and whether observed variation in rates is likely due to changes in biomass or changes in biomass-specific activity levels. The relationship developed between heterocystous cyanobacteria biomass and directly measured N_2 fixation was additionally used in conjunction with time series data of heterocystous cyanobacteria biomass collected by NCDEQ at four stations to estimate an approximate monthly time series of N_2 fixation from 2011 to 2020.

Estimates of lake-wide, annual N input due to N_2 fixation were calculated in two ways. The first method involved scaling up the direct measurements of N_2 fixation made in this project to produce a lake-wide estimate. The second method involved scaling up and averaging the monthly time series of N_2 fixation estimated based on heterocystous cyanobacteria biomass measured by NCDEQ at the four NCDEQ stations. Both methods accounted for the photic volume of areas of the lake represented by the available N2 fixation estimates and both estimates assumed a 12 h per day photoperiod when N2 fixation is possible. Interannual variability of the biomass-based (second method) annual N_2 fixation rates were compared against annual stream loads of N to investigate whether stream loads were related to N_2 fixation as would be expected if reduced N loads enhanced N limitation within the phytoplankton community.

Assessing nutrient limitation and effects of nutrient availability on N2 fixation:

Nutrient addition bioassay experiments were conducted at three creek stations during spring and summer 2021 to determine the limiting nutrient in the creek arms and to determine the extent to which N_2 fixation is impacted by P availability. For each experiment, triplicate Cubitainers were amended with the following treatments: a control with no added nutrients, nitrate addition, phosphate addition, and nitrate plus phosphate. Phytoplankton growth and N_2 fixation were assessed after a three-day incubation period. The control and P addition treatment were additionally reassessed after one week to determine the degree to which enhanced P availability can stimulate shifts toward N_2 fixing cyanobacteria taxa. This information is useful for determining the potential for P inputs to stimulate N_2 fixation and can provide a useful upper constraint for modeled N_2 fixation rates.

Characterizing the N mass balance:

Annual tributary loads of total N and total P for tributaries to Falls Lake and atmospheric deposition of N over the period 2006 to 2019 were taken from NCDEQ's 2021 Status Report of the Falls Lake Nutrient Strategy (NCDEQ 2021). Annual fluxes of total N and total P out of Falls Lake were calculated using the weighted regressions on time, discharge, and season (WRTDS) model on USGS gaged discharge (USGS gage 02087183) and monthly concentration data collected by NC DEQ's Ambient Monitoring System (station J1890000). Annual N inputs were calculated as the sum of tributary loads, atmospheric deposition, and N_2 fixation.

Net retention of N (TNret, units kg N/y) and P (TPret, units kg P/y) was determined as the difference between annual inputs and outputs through river flux. Under an assumption that net retention of P is due solely to sedimentation, the whole lake denitrification rate (DNF) can be estimated based on the ratio of N:P retention (N/Pret) and the average N:P mass ratio of the lake's surface sediments (N/Psed) which was estimated as 3.67.

Key Takeaways and Management Implications

1) Direct measurements of N_2 fixation indicate that N_2 fixation contributes less than 1% of total N inputs to Falls Lake. Estimated N_2 fixation based on the biomass of cyanobacteria capable of N_2 fixation is about 6% of tributary inputs. Both methods agree that

Sampling at Falls Lake.

N_2 fixation is a small percentage of total N_2 inputs which provides a justification for omitting the process in eutrophication models for Falls Lake.

2) Based on the mass balance and direct core measurements of denitrification it appears that denitrification is greater than N_2 fixation and that the balance of these microbial processes result in a net loss of N from Falls Lake. Net loss of N could help maintain N limited phytoplankton which is consistent with N limited growth observed in nutrient addition experiments conducted in spring and summer 2021.

3) Most of the N and P within Falls Lake are bound up in plankton biomass. Neither N or P is available in great excess and small additions of N commonly led to P limitation. P availability also appeared to be an important constraint on N_2 fixation. This situation of weak N limitation and the potential for stimulation of N_2 fixation by P suggests that dual management of N and P is warranted for preventing undesirable phytoplankton biomass in Falls Lake.

The full Defining the Balance Between Cyanobacterial Fixation and Denitrification report can be found at:
https://nutrients.web.unc.edu/

Cyanotoxin Presence and Year-round Dynamics

RESEARCH QUESTIONS

1. Are cyanotoxins present in Falls Lake? When during the year are they present and where?

2. Can spatiotemporal patterns in cyanotoxins be linked to environmental conditions?

3. Which potential toxin-producing cyanobacterial taxa are present in Falls Lake? Does their spatiotemporal distribution link to toxin patterns and/or environmental factors?

RESEARCH METHODS

From July 2019 to December 2021, at 11 stations across Falls Lake researchers conducted monthly surface sampling in collaboration with the NC Department of Environmental Quality (NCDEQ). Surface samples were collected to determine chlorophyll-a, dissolved toxins, particulate toxin concentrations (microcystin, anatoxin, cylindrospermopsin, saxitoxin), and DNA for high-throughput sequencing. Passive in situ toxin sampling devices were deployed at a subset of 4 stations across the lake to measure the accumulated toxins. Environmental, meteorological, and hydrological data are analyzed for relationships with cyanobacterial and toxin dynamics.

FINDINGS

Maximal toxin concentrations from monthly collections did not exceed regulatory thresholds established by the World Health Organization. However, the accumulated dissolved toxin levels, detected by the passive in situ samplers indicated that monthly sampling is likely insufficient to document the full range of toxin dynamics. Monthly sampling may well have missed peak toxin concentrations or the occurrence of multiple events between sampling efforts.

Monthly, relatively low, microcystin (MC) levels did not align with the moderate risk of health effects from MC exposure suggested by the WHO based on chlorophyll-a levels. Thus, algal biomass alone is not a reliable indicator of cyanotoxin exposure risk in Falls Lake.

Co-occurrence of more than one cyanotoxin was observed in 14% of dissolved, 36% of particulate, and 43% of accumulated dissolved toxin samples alerting to the potential for chronic exposure to multiple toxins, especially during fall and summer seasons and in lower and tributary regions.

MANAGEMENT IMPLICATIONS

- Research suggests that the eutrophic status of Falls Lake makes it prone to experience intensification of cyanobacterial harmful algal blooms in response to climate change.

- An increasing number of studies have confirmed the ubiquitous nature of cyanotoxins—further research is necessary to characterize the conditions that favor toxin production.

- Linkages between cyanobacterial community composition and the occurrence of varying toxins warrants further analyses.

RESEARCHERS

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Overview

Cyanobacterial Harmful Algal Blooms (CyanoHABs) in North Carolina freshwater systems can adversely impact drinking water, fisheries, tourism and food web resilience. The main goals of this study are to examine the spatiotemporal dynamics of CyanoHABs in relation to cyanotoxins in Falls Lake. We determined algal growth together with cyanotoxin presence at multiple sampling sites throughout the lake to identify environmental conditions that favor algal growth and/or toxin production ("hot spots"). Furthermore, we focused on identifying the cyanobacterial taxa that dominate throughout the lake system and are associated with toxin presence and/or certain environmental conditions. All aspects of this study have been completed, except the analyses of sequencing data.

Sampling

Monthly surface sampling from July 2019 through December 2021, in collaboration with the NC Department of Environmental Quality (NCDEQ), encompassed 11 stations across Falls Lake. Sampling did not occur in January or February of 2021 due to COVID-19. Surface samples (0 – 0.25 m) were collected in 1L PETG bottles and then transported to the lab within ~ 6 hours and processed to determine chlorophyll-a (chl-a), dissolved toxin, and particulate toxin concentrations and for DNA extraction and sequencing. As part of the NC Division of Water Resources (NCDWR) Ambient Monitoring Program, samples were also collected (depth-integrated from surface to 2x Secchi) to determine concentrations for ammonia (NH3), nitrite plus nitrate (NO2+NO3), total Kjeldahl nitrogen (TKN), total phosphorus (TP), temperature, turbidity, pH, dissolved oxygen (DO), and conductivity (NCDWR standard operating manual). Solid Phase Adsorption Toxin Tracking (SPATT) devices were deployed at a subset of 4 stations across the lake to measure accumulated toxins.

Management Implications

This study is the first to show that cyanobacterial communities in Falls Lake are linked with the recurrence of multiple cyanotoxins throughout the year and across several lake regions. These findings fall in line with an increasing number of studies that have confirmed the ubiquitous nature of cyanotoxins, their simultaneous presence in varying environments and the need for further research to characterize the conditions that favor toxin production. The continued development and employment of highly sensitive toxin-tracking approaches (e.g., SPATTs), together with an expanding tool-kit for genomic testing, will be essential for further examination of cause–effect relationships and providing the knowledge needed to predict the likelihood for current and future toxin exposure via varying exposure pathways in Falls Lake. Our study clearly demonstrates that further monitoring and expanded research (e.g., food web contamination study and determination of MC congener composition) in Falls Lake is warranted to protect the lake's dedicated uses. Falls Lake provides drinking water for over 500,000 people and serves as a significant recreational site for swimming, boating, and fishing.

Water sampling at Falls Lake.

Guidelines by the WHO to assess risks (low, moderate and high) from MC exposure are based on either direct measurements of MC concentration, the determination of chl-a or cyanobacterial density. However, applying these three metrics, a water body can be at risk based on one, but not all, of these criteria. For instance, for over 1100 lakes in the US, agreement for risk assessment based on all three parameters was only observed for 27% of the systems. Our findings from Falls Lake agree with these reports and indicate that MC exposure risk based on chl-a measurements (moderate risk) do not agree with those based on actual microcystin measurements (low risk). Thus, the inclusion of toxin measurements when chl-a values indicate active bloom conditions is a critical tool for continued monitoring across Falls Lake.

Another major knowledge gap that has not been addressed for Falls Lake but warrants further study, is the congener composition of MC as the most prevalent toxin detected. Cyanobacteria can potentially produce 100s of MC congeners of varying toxicity but bloom events are typically associated with a subset of dominant congeners. Environmental testing, rodent, and human toxicity studies, however, have primarily focused on a single MC congener (MC-LR). A recent study by our research group within the Albemarle Sound region indicated that MC-LR might be present together with less toxic variants including MC-RR or MC-YR. This information is key since all WHO guidelines for drinking water, recreation and consumption are based on MC-LR and none of the co-occurring MC congeners. Gaining an understanding of variability in MC concentrations and congener composition in Falls Lake as well as in tested fish is needed to accurately assess exposure risks from lake uses. Additional key findings in this study alert to other important issues related to CyanoHABs in Falls Lake that, if unaddressed, may have more severe implications for public health.

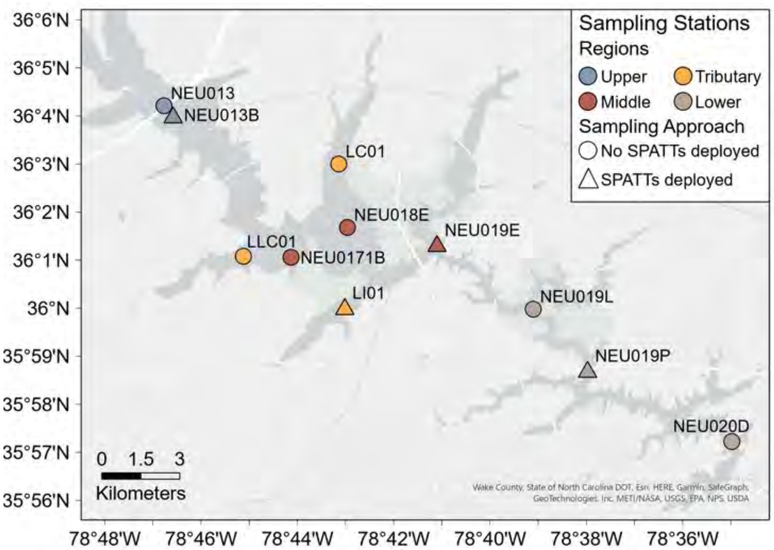
1) While monthly discrete toxin concentrations did not rise above regulatory thresholds for MC, the detection of multiple types of cyanotoxins currently prevent an accurate assessment of chronic exposure to multiple toxins (including MC congener mixtures).

2) The results on accumulated dissolved toxins based on in situ tracking devices indicated that our monthly sampling approach may well have missed peak toxin concentrations or the occurrence of multiple events between discrete sampling efforts.

3) Toxin accumulation based on passive toxin trackers are a good indicator of the potential for active toxin accumulation through the food web. There is currently no information on whether commonly caught fish from Falls Lake are positive for cyanotoxins.

A comprehensive review of CyanoHAB research suggests that the eutrophic status of Falls Lake, make it prone to the intensification of blooms in response to climate change and, thus, increasing risk of toxin exposure. Given our results so far, we highly recommend continued, higher-frequency monitoring of cyanotoxins in Falls Lake at least within the middle/tributary and lower portions of the lake. In addition, monitoring should expand to determine MC congener composition in both water (intracellular and dissolved fractions) as well as in aquatic organisms commonly caught for human consumption. Since this is the first comprehensive study that focuses on cyanotoxin dynamics in Falls Lake we believe the information to be of value for residents, monitoring agencies and recreational users. We hope our findings will inform future investigations, adapted monitoring approaches and an expansion of targeted testing to accurately assess both current and future risks to lake uses and public health for Falls Lake.

The full Cyanotoxin Presence and Year Round Dynamics report can be found at: [*https://nutrients.web.unc.edu/*](https://nutrients.web.unc.edu/)



Map of Falls Lake sampling stations. Stations are color coded by region. Stations with triangles indicate deployments for in situ deployments of passive toxin samples or Solid Phase Adsorption Toxin Tracking (SPATT) units.

Policy in Focus: The Stormwater Billion Dollar Question

The current Falls Lake Rules rely substantially on the removal of nutrients from stormwater to bring the Lake into compliance with the Water Quality Standard (WQS) for chlorophyll-a. The estimated cost to reduce nutrient loading from within Existing Development to said standard is approx. $1.087 billion. Pending such a large community investment, new insight from the Upper Neuse River Basin Association (UNRBA) and the Collaboratory raises questions as to whether this is the most efficient and cost-effective strategy to protect the Lake's designated uses.

Firstly, the stability of Falls Lake over the past decades suggests that the current WQS, which is being exceeded each year, is not an accurate metric for the overall health of the reservoir. Thus far, these exceedances have not resulted in measurable adverse impacts upon the Lake's uses; it has remained drinkable, fishable, and swimmable. Therefore, there should be an evaluation of whether a site specific WQS would be more beneficial. This site-specific WQS would balance the designated uses of the reservoir, unlike the current standard which ignores the fishing use as it asserts no minimum nutrient/algae level.

It is dubious whether the use of the Lake for fishing would even remain intact if chlorophyll-a succeeded in being reduced to the current WQS. Instead, the current WQS is an arbitrary quantity not reflective of the watershed's hydrology and natural nutrient cycling. Since the Lake's uses currently appear to be met, it supports the conclusion that the reservoir's existing chlorophyll-a concentrations are supportive of those uses, and that the revised Falls Lake Rules should establish a nutrient reduction budget that continues to protect all uses, including fishery use.

Secondly, the emphasis which the current Rules place upon the removal of nutrients from stormwater to bring the Lake into compliance is both impossible and no longer feasible. UNRBA modeling demonstrates that the nutrient loading reductions required by the Rules cannot be achieved even if the existing development were removed and replaced with forests. This is due to unmanaged lands, such as forests, being the largest source of nutrient loading for Falls Lake. In comparison, Urban Development, the more appropriate term for Existing Development, is estimated to generate only 12% of TP and 15% of TN. In addition, the authority of local governments to impose requirements related to stormwater treatment has been curtailed severely by the Legislature. Legislative prohibitions now exist against mandatory local programs that require certain development reductions and retrofits. The withdrawal of this power to regulate existing development effectively repeals the Rule. Therefore, in light of both scientific findings and legislation, the current Rules place unjustifiable emphasis on stormwater treatment as a method of nutrient reduction.

The Existing Development rule, and its basis of load reduction calculation, is flawed and should be revised substantially, if not eliminated. Setting a near-term plan for further reduction should be delayed until all relevant information can be evaluated; in the interim, the IAIA program should be continued. The New Rules should allow for the use and recognition of conservation easements or acquisitions in addition to grant programs to assist with green infrastructure, agricultural improvements, and other voluntary efforts to protect water quality. In conclusion, the current Rules, due to their inadequacy, should be significantly revised or repealed.

This Policy in Focus: Stormwater the Billion Dollar Question is a summary of research conducted by Dan McLawhorn, a legal and policy consultant for the Falls Lake study.

The full report can be found at https://nutrients.web.unc.edu/

Estimating Nutrient Loads from Streambank Erosion

RESEARCH QUESTIONS

Is streambank erosion a significant source of nitrogen and phosphorus entering Falls Lake?

Can hotspots for streambank erosion be identified throughout the watershed?

Are the estimates from the Upper Neuse River Basin Association's (UNRBA) model and the USGS (US Geological Survey) NC Survey SPAtially Referenced Regression on Watershed (SPARROW) model reasonable for total suspended solids (TSS), total nitrogen (TN) and total phosphorus (TP) loads (quantity of each nutrient entering Falls Lake) from streambank erosion?

RESEARCH METHODS

In 2022, NC State University (NCSU), Biological & Agricultural Engineering (BAE) Department began evaluating the potential sediment and associated nutrient inputs arriving to Falls Lake from streambank erosion. Streambanks were assessed at 111 locations throughout the watershed including a range of streambank conditions from stable to severely eroding. Erosion rates were monitored for 7 to 9 months at 28 locations exhibiting active erosion. For a period of one year, flow, turbidity (water clarity), total suspended solids (TSS) and total phosphorus (TP) were measured at five subwatersheds (small watersheds within a single, larger watershed) to generate TSS and TP loads.

Field-based assessments of streambank condition and erosion rates were used to develop three models to estimate 1) potential locations where erosion was occurring, 2) the height of the streambank and 3) the rate of streambank erosion at 100 feet increments for all the streams in the Falls Lake watershed. Average, upper, and lower estimates of TSS and nutrient loads were estimated for the five study watersheds as well as for the entire Falls Lake watershed.

FINDINGS

Out of the 111 stream reaches assessed, on average 45% of the banks were stable, 30% had minor erosion and 25% were severely eroding. Twenty-five of the 28 cross-sections monitored had measurable erosion with five of them eroding on both sides of the stream. The rate of average bank retreat for eroding banks ranged from 0.1-1.7 ft/yr. Our modeled range of TSS load from streambank erosion for Falls Lake was much higher than the load estimated by the Upper Neuse River Basin Association (UNRBA) load and the SPARROW estimates for streambed erosion. Our lower and upper limits were almost 10 to nearly 40 times greater than the SPARROW estimate. Our model loads were also much higher than the UNRBA delivered load, with our lower limit 3.7 times the UNRBA estimate.

Total TSS loads based on NCSU water quality monitoring, and estimated by SPARROW and UNRBA models, were in the low range of the annual loads calculated from past USGS monitoring. Total TP loads were also on the low range based on past USGS monitoring for NCSU and SPARROW estimates. The NCSU water quality monitoring loads were likely on the low end of the range due to a lack of large storm events occurring during the monitoring period of the study.

MANAGEMENT IMPLICATIONS

The models developed in this study provide straightforward procedures for indicating locations where potential stream restoration and enhancement activities could be implemented. Maps developed by this effort indicate areas where higher sediment and nutrient loading were predicted that could be used to validate predictions and target areas for restoration and stabilization efforts.

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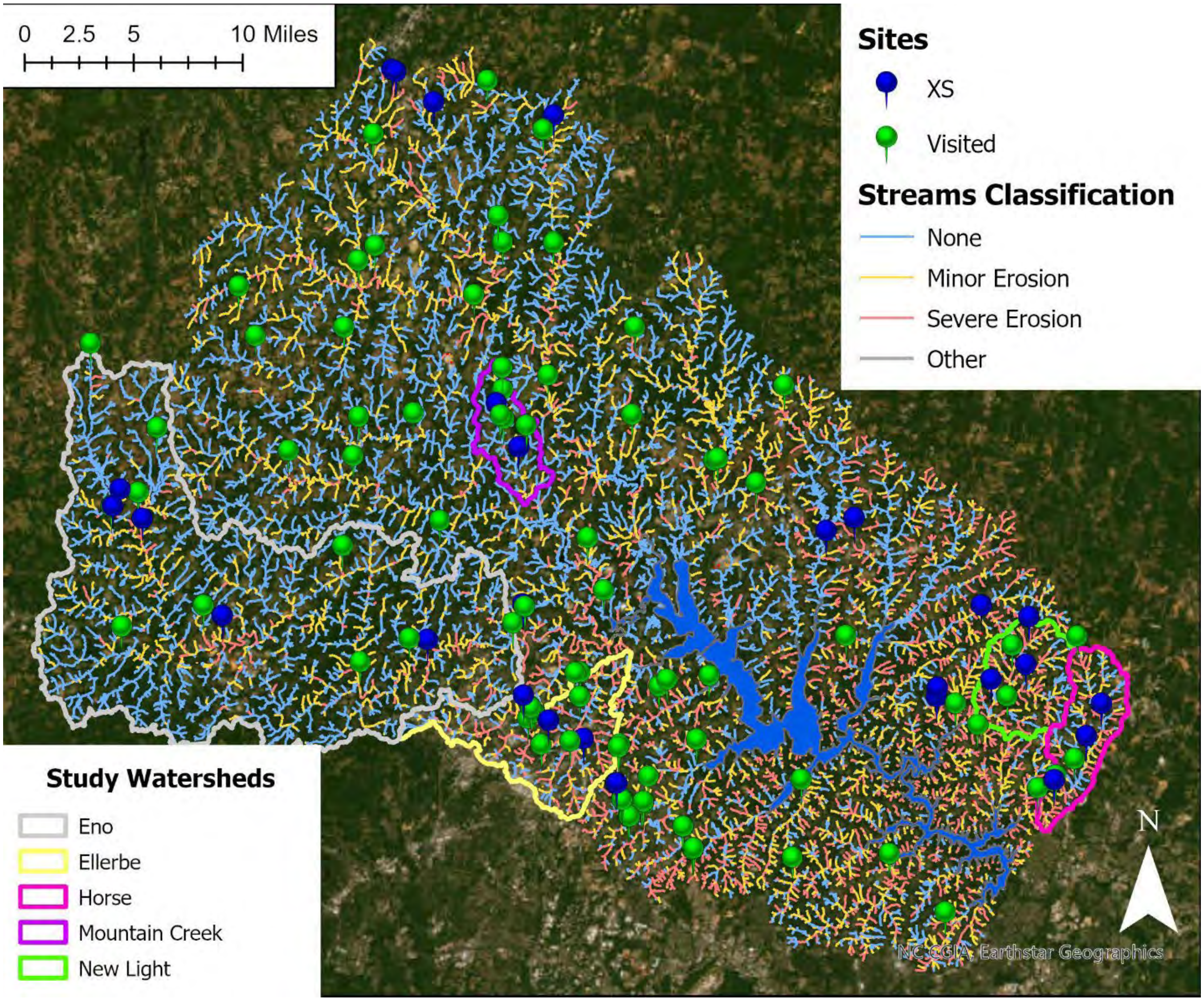
Background and Study Approach

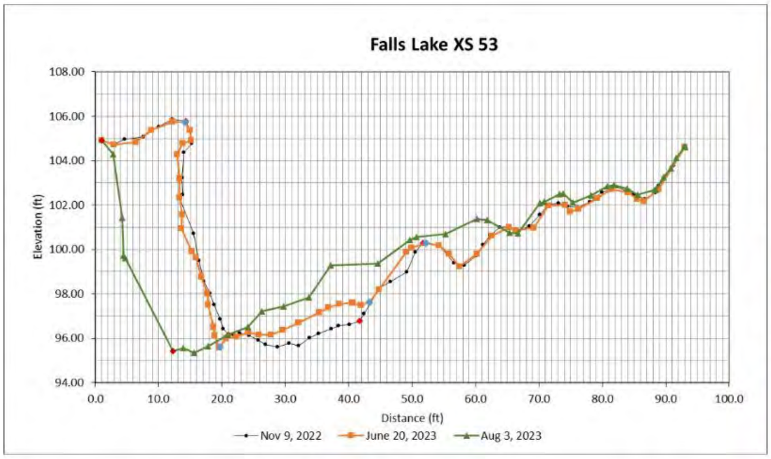
In some watersheds, streambank erosion can be the most significant process contributing to in-stream sediment loads. Sediment from streambanks also can serve as a dominant source of nutrient pollution. Eroded streambank sediments have been found to contribute between 10-40% of total phosphorus load in many watersheds. In 2022, NC State University (NCSU), Biological & Agricultural Engineering (BAE) Department evaluated the potential nutrient inputs that could be arriving to Falls Lake from streambank erosion. Geospatial analyses, inventory of streambank condition, assessment of streambank erosion rates, analysis of nutrient levels in streambank soils, field-based water quality monitoring and extensive statistical analyses were conducted to estimate the potential nutrient loads from eroding streambanks upstream of Falls Lake.

Streambanks were assessed at 111 locations throughout the watershed including a range of streambank conditions from stable to severely eroding. Erosion rates were monitored for 7 to 9 months at 28 locations exhibiting active erosion using repeat cross-section surveys. Soil samples were collected from the streambanks at all cross-sections and analyzed for nutrient content and bulk density.

For a period of one year, NCSU also measured flow, turbidity, total suspended solids (TSS) and total phosphorus (TP) at five subwatersheds to generate TSS and TP loads. Relationships between turbidity and TSS and TP were developed from this data. The loadings were also used to estimate the total proportion of streambank erosion loads to total TSS and TP loads, which also include land-based sources of sediment for the five subwatersheds. Loads were compared to US Geological Survey SPAtially Referenced Re-

Project site locations and study watersheds.





Bank Retreat	Nov 22 - June 23		June 23 - Aug 23	
	(ft)	(ft/yr)	(ft)	(ft/yr)
Avg	0.7	1.2	9.8	81.1
Min	0	0	7.5	62.3
Max	2.1	3.4	13.9	115.4

Streambank erosion is a significant source of the external nutrient load for Falls Lake.

gression on Watershed (SPARROW) and Upper Neuse River Basin Association (UNRBA) total loads. Long-term water quality data measured by USGS at three of the flow gauging stations was used to develop total loads for TSS and nutrients for comparison.

Field-based assessments of streambank condition and erosion rates were combined with detailed geospatial mapping and modeling of land use and landforms to develop three models to 1) estimate potential locations where erosion was occurring, 2) the height of the streambank and 3) the rate of streambank erosion at 100 feet increments for all the streams in the Falls Lake watershed. Results of all models were combined with measured soil densities to generate a range of predicted sediment loading for each catchment in the watershed. Delivered loads were estimated by multiplying the incremental load by a phosphorus delivery percentage estimated by the UNRBA initial watershed trapping analysis where sediment delivery was assumed to be equivalent to phosphorus delivered. Soil TN and TP concentrations were also used to generate predictions of nutrients for streambank erosion. Estimates of TSS and nutrient loads were estimated for five study watersheds as well as for the entire Falls Lake watershed.

Findings

Out of the 111 reaches assessed, on average 45% of the banks were stable, 30% had minor erosion and 25% were severely eroding. Twenty-five of the 28 cross-sections monitored had measurable erosion with five of them eroding on both sides of the stream. The rate of average bank retreat for eroding banks ranged from 0.1-1.7 ft/yr.

Our modeled estimates of TSS load for Falls Lake were far greater than the UNRBA load and the SPARROW estimates for streambed erosion. Our lower and upper limits were almost 10 to nearly 40 times greater than the SPARROW estimate. Our model loads were also much higher than the UNRBA delivered load, with our lower almost 4 times the UNRBA estimate. Our overestimation of TSS incremental and delivered load is likely due to several factors: double the length of channels identified in the model, a bias towards selecting the most severely eroding cross-sections for monitoring, an overprediction of eroding banks from the erosion classification model and high delivery ratios that overlook the loss of sediment within channels. Despite our much larger TSS loading estimate, the UNRBA TP from streambanks is about 1 to 3 times our TP estimates for the lower and upper limits, respectively. Our TN delivered estimate was 8 times larger than the UNRBA load. Even at this higher level, streambank erosion is estimated to comprise only about 6% of the total TN load. Because our nutrient loads were close to SPARROW and UNRBA despite much larger estimates of sediment volume, this indicates that SPARROW and UNRBA may overestimate soil nutrient concentrations for streambanks.

When comparing the proportion of sediment and nutrient loads that are from streambank erosion for the five study subwatersheds, our estimates for Ellerbe and Eno are closer to UNRBA and SPARROW. However, our estimates for Horse, Mountain and New Light were substantially larger with UNRBA tending to estimate nearly 0 for the sediment and nutrient loads. Total TSS loads based on NCSU water quality monitoring and estimated by SPARROW and UNRBA models were in the low range of the annual loads calculated from past USGS monitoring at Ellerbe, Eno and Mountain creeks. Total TP loads were also on the low range based on past USGS monitoring for NCSU and SPARROW estimates, but UNRBA estimates were similar to the range of loads calculated based on past USGS monitoring for Eno and Ellerbe but were low for Mountain Creek. The NCSU water quality monitoring loads were likely on the low end of the range due to no large storm events occurring during the monitoring period of our study.

Management Implications

Both the UNRBA and SPARROW models estimate that approximately 30% of all sediments delivered to Falls Lake are coming from unstable stream reaches and that these streams are contributing between 14.5 to 16% of the total TP load but only 0.8% of the TN load (UNRBA only). Our modeled TSS loads, which are derived from watershed, topographic and empirical data and function to predict the presence of erosion, height of streambank, and rate of erosion indicate that the estimates from these models are not unreasonable and that loads from streambank erosion could potentially be higher. Further, by leveraging terrain data, our models provide desktop procedures for indicating locations where potential stream restoration and enhancement activities could be implemented to target reductions in turbidity, TSS and associated nutrients. Most of the catchments with the highest loads are closer to the outlet of the watershed. Our study effort developed maps indicating areas of predicted higher sediment and nutrient loading that could be used to target areas for stream restoration and stabilization efforts. Our estimates reveal that several catchments in the Horse and New Light subwatersheds located in the far eastern portion (Wake and Granville County) of the Falls Lake watershed are likely contributing higher volumes of sediment and nutrients to the lake than basins located further west. The areas with higher sediment loads also tended to be more developed like Wake and Durham County. Streams in Wake and Granville County have bank heights at least 2 times higher than the bankfull height indicating incision and active erosion. These areas could be targeted for restoration and/or streambank repair and enhancement activities.

Restoration efforts have been shown to successfully improve bank stabilization and prevent sloughing and further incision of the channel. Bank stabilization efforts focused on protecting the bank toe-region have been shown to reduce erosion by 90%. And simulations for some watersheds by others have indicated that streambank stabilization could provide the greatest potential for the prevention/ removal of TP over other restoration practices. Restoration activities could also afford other habitat and water quality related benefits. Detailed economic analysis is recommended to compare the cost of repairing these streams or their eroding streambanks against reducing other sources of sediment and associated phosphorus to optimize any investments targeted at reducing negative impacts to the water quality of Falls Lake.

Future steps could be taken to field validate and improve the models developed by our study. The erosion classification model is the worst performing model, likely due to the spatial distribution of the data used to build the model. As seen from the flow data, relatively few very large storms occurred during the monitoring. To fully capture the range of flow conditions (dry, wet and extreme events) long-term monitoring of erosion rates is required. Additional cross-sections, especially for minor erosion, could help to fill in the missing gaps in the current models. Further exploring delivery ratios could provide better insight into the sediment transport and dynamics within the watershed. To better understand the transport capacity of streams, sediment grain size analysis of bank material is also recommended as sand is more likely to be deposited within the channel whereas fines (silt and clay) have a much higher chance of reaching Falls Lake.

For the full Estimating Nutrient Loads from Streambank Erosion visit: https://nutrients.web.unc.edu/

Impoundment Ecosystems and Global Organic Carbon Cycling

RESEARCH QUESTIONS

1) How do total suspended matter (TSM) concentrations vary during an annual period and what is the relationship between TSM, particulate organic concentrations (POC) and water discharge rates?

2) How have the sediment and carbon accumulation rates changed over the lifetime of the reservoir?

3) What are the main sources of the organic carbon accumulated in Falls Lake bottom sediments?

4) How do reservoirs compare to other significant carbon depocenters such as Blue Carbon environments (marshes, mangroves, seagrass), natural lakes, and estuaries?

RESEARCH METHODS

Water samples were collected approximately every two weeks between July 2019 and April 2020 from the Eno, Flat, and Little rivers and Ellerbe creek. Collectively these sources supply ~70% of the water to Falls Lake. A sediment rating curve was constructed and samples of suspended particulates were analyzed for each input. Sediment cores were also collected, and each core was extruded and subsampled at 1cm intervals with each interval analyzed for 210Pb. 210Pb radioisotope was used to quantify sediment and carbon accumulation rates. Cores were collected at 8 locations starting at the upper reservoir closest to freshwater inputs.

FINDINGS

• Sediment Accumulation Rates (SAR), Carbon Accumulation Rates (CAR), and %OC have remained relatively constant over time; it can be assumed that watershed inputs have not varied greatly since the reservoir's creation. However, this may change in accordance with future land use changes as the area continues to develop.

• For the three rivers, most sources of organic carbon originate from soil organic matter (SOM). Ellerbe Creek, which has a large proportion of urban environments, also has indications of human inputs such as fertilizer, septic, sewage.

• Based on sediment core content, carbon accumulation in the reservoir is primarily from SOM sources rather than from seasonal algal blooms.

MANAGEMENT IMPLICATIONS

• The results of this study indicate Falls Lake is comparable and, in some cases, may exceed the CAR of many high carbon burial ecosystems, such as Blue Carbon environments.

• The potential of reservoirs as showcased by Falls Lake, combined with the increasing prevalence of reservoirs globally, demonstrate the growing need for more rigorous and repeatable data to quantify reservoirs as major terrestrial carbon sinks.

RESEARCHERS

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Background

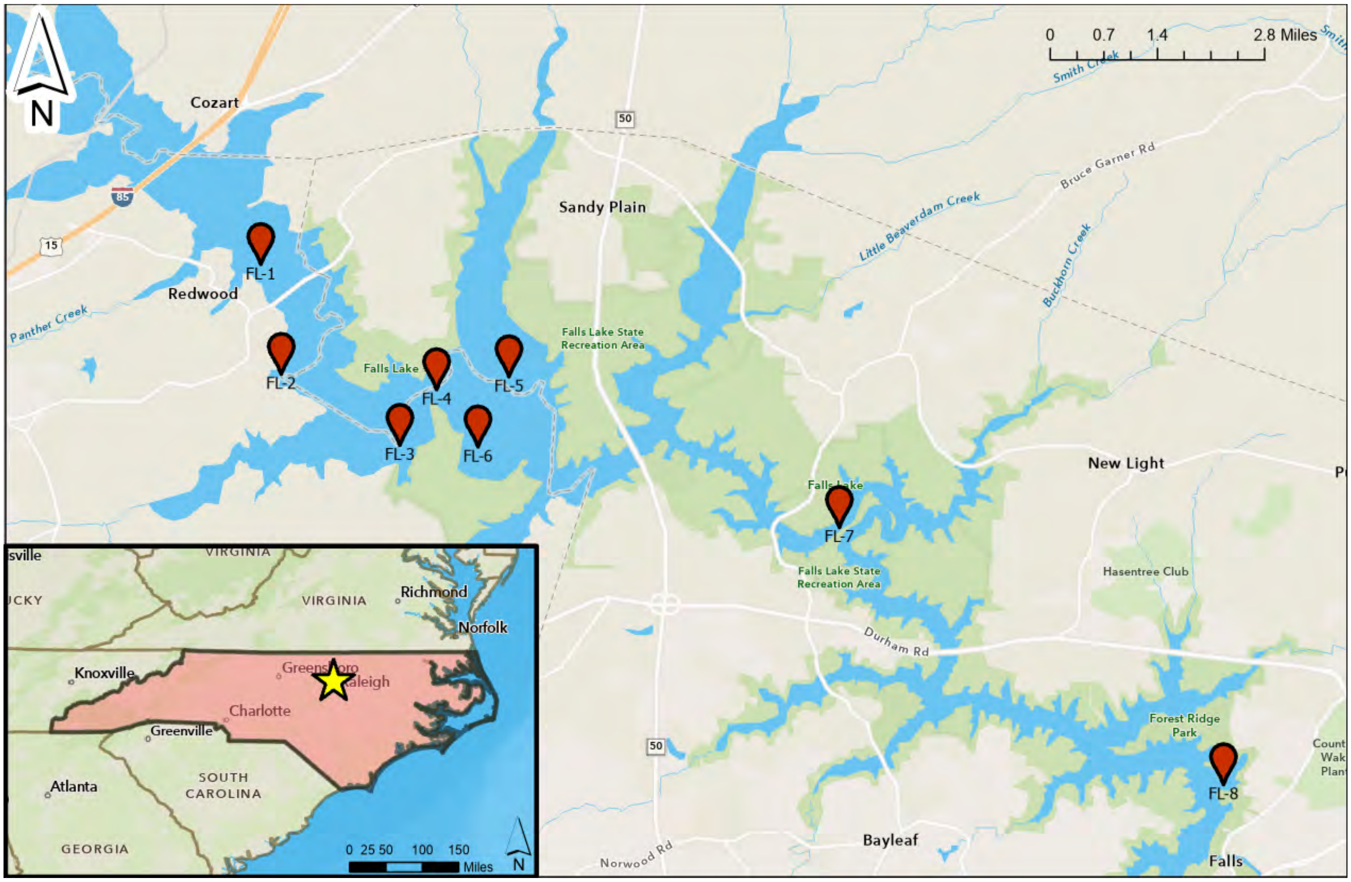
Particulate materials play a dominant role in the transport of vital elements in river systems. Globally, a large fraction of riverine flux is in particulate form (Phosphorus~ 85%, Nitrogen ~40-85%, Organic Carbon ~ 65%). Prior to this study, very little has been documented regarding sediment input into Falls Lake. The overall objective of this study was to better understand sediment fluxes associated with Falls Lake, ranging from rates of sediment inputs to the fate of particulate materials within the lake on time scales from seasonal to decadal. The fate of many important particle-associated materials, such as carbon, nitrogen, and contaminants, are closely tied to the fate of particles in Falls Lake and this tells their story.

The four major inputs to Falls Lake (Flat River, Eno River, Little River and Ellerbe Creek) make up approximately 70% of the freshwater input to Falls Lake. However, no rating curves have been constructed to predict suspended sediment concentration loads based on water discharge, a parameter which is readily available daily via USGS reporting stations online. Even less is known about deposition rates (spatially and temporally) within Falls Lake. Based on sediment thickness there was general impression that sediment deposition rates are higher in the upper lake than in the lower lake. However, no quantitative measures of sedimentation rates existed prior to our study. Sedimentation rates, (derived using the naturally occurring tracer ^{210}Pb) establish sediment histories that provide critical information needed to evaluate the flux of particle associated materials such as carbon, nutrients (N and P) and contaminants during the time between the present and when the reservoir was formed.

During the past decade, many environmental and climate scientists have raised a central question regarding the importance of inland waters to global organic carbon cycling and climate change. One of the seminal papers for this research postulated, based on their study, that agriculturally impacted impoundments like Falls Lake may bury more organic carbon (OC) than the oceans and 33% as much as world's rivers deliver to the sea. This assertion galvanized the research community and generated world-wide interest in lakes and reservoirs and their influence on global organic carbon and climate change.

This study focused on a high resolution record of sediment and carbon fates over a multiyear period. The spatial aspects of this study were addressed by examining four rivers and creeks that

Locations for cores collected.



supply most of the particulate materials to the lake. These input waters vary in terms of the size of their watersheds, the nature of land use within their watersheds (urban, forest, agriculture etc.) and their water discharge rates. The temporal aspect of this study was addressed by collecting river/creek water samples approximately every month over an annual period. Sedimentation rates and carbon concentration profiles measured within cores collected throughout Falls Lake were used to document rates of sediment and carbon burial during the past 40 years since the reservoir was formed.

The dramatic increase in CO2 emissions during the past century means that the storage of organic carbon in reservoirs must increase substantially, if carbon accumulation in reservoirs is an effective mechanism for global carbon sequestration. Surprisingly, no data exists in the peer-reviewed literature to test this. Results of this study indicates that there is no increase in carbon burial to keep up with CO2 emissions. Collecting endmember source samples and reservoir bottom sediments for stable isotope determinization (15N and 13C) and C/N concentrations were used to determine the dominant source of organic carbon buried in the reservoir. We determined that carbon burial rates in Falls Lake are among the highest of any depositional environments (including coastal "blue carbon" environments), and that the source of the organic carbon buried was directly from the watershed.

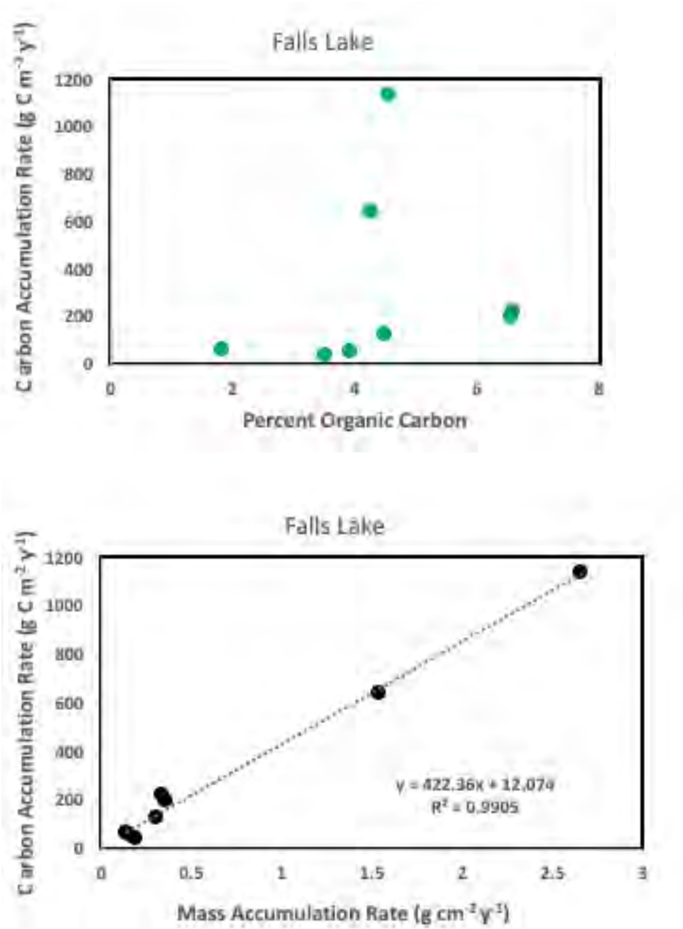
Management Implications

The results of this study can be used to answer a few overall questions about carbon accumulation in this reservoir that have management implications:

(a) What drives carbon accumulation?

Many possible factors are potential drivers of carbon accumulation within an aquatic system. The major drivers may vary significantly based on the ecosystem studied. Based on the factors used to calculate carbon accumulation, CAR is the product of MAR * f, where f is the fraction of organic carbon (%C ÷1000). Therefore, the two potential major drivers for carbon accumulation must be either sediment accumulation rate or organic carbon content. All CAR values are plotted against %OC and MAR in Figure 15, which shows a very strong correlation between CAR and MAR (R2= .9905) and no discernable correlation between CAR and %OC. This suggests MAR is a very strong control on CAR within Falls Lake, likely because of the dominance of an allochthonous source of material from the watershed.

Carbon Accumulation Rate vs. POC and MAR (cores FL1–FL8).



(b) Have CARs changed over the past 40 years?

Downcore profiles within Falls Lake indicate that CAR has not changed significantly since the reservoir's construction in the early 1980s. No core shows a significant, progressive increase that would be consistent with a response to rising atmospheric carbon concentrations, nor do they show a significant basin-wide trend. These trends are consistent with the idea that MAR controls CAR. Because SAR and MAR have remained relatively constant over time throughout Falls Lake, we can also assume watershed inputs have not varied greatly since the reservoir's creation. However, this steady input may potential vary in the future with regional land use changes as the area continues to be a hub of human development. Ongoing deforestation and rises in stormwater runoff resulting from urbanization could result in increasing erosion within the watershed and provide more allochthonous materials to be potentially stored within the reservoir.

(c) How do reservoirs compare to other significant carbon depocenters such as Blue Carbon environments (marshes, mangroves, seagrass), natural lakes, and estuaries?

Blue carbon environments have recently been recognized as ecosystems that are high in carbon sequestration and therefore have received significant attention that has resulted in numerous publications in recent years. Similarly, natural lakes and estuaries have also been studied extensively for their carbon sequestration potential. Manmade reservoirs have not experienced the same level of attention and have largely been underappreciated as terrestrial carbon sinks. The results of our study indicate Falls Lake is comparable and, in some cases, may exceed the CARs of many of these high carbon burial ecosystems, which range in mean values from 138 g C m-2y-1 for seagrass beds to 226 g C m-2y-1 for mangroves. The mean CAR of cores collected in Lake range from 43 to 1139 g C m-2y-1, with a mean value of 313 g C m-2y-1, on par with the reported CAR values for various blue carbon environments.

The indication is that reservoirs are comparable as carbon sinks to ecosystems that have received significantly more attention. Falls Lake shows higher CARs even in the areas of lowest accumulation than recent values for global lake carbon accumulation, which have a mean of 22 g C m-2y-1. This suggests that the unique dynamics of reservoirs compared to outwardly similar natural lakes makes them much more accommodating for sediment and carbon burial. The potential of reservoirs showcased by Falls Lake, combined with the dramatically increasing prevalence of reservoirs globally, demonstrate the growing need for more quantitative, rigorous, and repeatable data to rigorously quantify reservoirs as major terrestrial carbon sinks.

The full Impoundment Ecosystems and Global Organic Carbon Cycling report can be found at: https://nutrients.web.unc.edu/

Fate and Transport of Nutrients from Onsite Wastewater Systems

RESEARCH QUESTIONS

1. Do onsite wastewater systems (OWS) increase nutrient concentrations in and nutrient loads to streams draining to Falls Lake?

2. How do malfunctioning OWSs affect water quality in groundwater near the drainfield and streams located hydraulically downgradient from the drainfield?

3. Does the type of carbon source affect nitrogen treatment in bioreactors? Are denitrifying bioreactors a feasible nutrient management strategy for OWS in the Falls Lake Watershed?

RESEARCH METHODS

Question 1: sampling locations were selected based on OWS characteristics across a range of hydrogeological settings in sub-watersheds draining to Falls Lake. Water samples were analyzed for nitrogen (TDN) and phosphate (TDP) concentrations.

Question 2: three residential sites were selected, two of which experienced malfunction. Water quality measurements included wastewater (from tanks), drainfield groundwater, downgradient groundwater, and nearby streams.

Question 3: a pilot-scale bioreactor study was conducted to evaluate the nitrate treatment efficiency of 3 carbonaceous media: roasted peanut hulls, pine bark, and assorted species of woodchips.

FINDINGS

Sand filter systems significantly underperformed compared to conventional systems. OWS have the potential to be significant nutrient sources to the Falls Lake Watershed. Streams which drained sub-watersheds served by OWS contained TDN concentrations 4.5x greater than that of predominantly sewered sub-watersheds. Malfunctions can be significant nutrient and E. coli sources to shallow groundwater and surface water, especially if riparian buffers lack well-established vegetation. Drainfields reached nutrient concentrations up to wastewater strength. Nitrate concentrations decreased by up to 50% after flowing through the bioreactors. The highest TDN concentration reductions were observed in pine bark bioreactors followed by peanut hulls and woodchips.

MANAGEMENT IMPLICATIONS

• Single-pass sand filter systems can be significant sources of nutrients, especially TDN, to water resources and are not recommended.

• Planning efforts should aim to keep OWS densities to be less than approx. 1 system/ha. Where high densities of OWS are found there should be consideration of retrofit management practices, such as the implementation of sewer infrastructure or the addition of bioreactors.

• Collaboration is needed between local county health departments and the NC Department of Health and Human Services to develop a central repository of GIS data for OWS. This information, in addition to community efforts, should be used to identify and repair malfunctioning OWS.

RESEARCHERS

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Impact of Onsite Wastewater Systems

Onsite wastewater systems (OWSs) often serve as the primary means of wastewater treatment for rural and suburban areas across North Carolina. In NC, there are an estimated 2 million systems in operation. In the Falls Lake Watershed, there are an estimated 50,000 OWSs based on efforts by Brown & Caldwell who partnered with Durham, Franklin, Granville, Orange, Person, and Wake Counties and the State of North Carolina to identify their locations within the watershed. There are an estimated 126,000 residents within the Falls Lake Watershed that rely on OWS for wastewater treatment (50,000 OWS * 2.52 people per household. These OWSs have potential to deliver nutrients to groundwater and surface waters, which may ultimately discharge to Falls Lake. Thus, there is a growing need to quantify fate and transport of OWSs within the Falls Lake Watershed to evaluate their contributions to nutrient loading to the lake.

The most common type of OWS in the Falls Lake Watershed is the conventional OWS that uses gravity distribution to store, treat, and dispose of wastewater. Wastewater is stored in the drainfield until it infiltrates the soil where most of the treatment occurs. While conventional OWSs are economical, they are not designed for complete removal of nutrients and can be a source of nutrients to groundwater systems. Furthermore, groundwater can transport nutrients to surface waters in hydrogeological settings where groundwater flowpaths facilitate baseflow discharge to streams and direct groundwater inputs to lakes.

Nutrient treatment efficiency by the OWS is an important factor that affects nutrient loading to water resources. Numerous factors influence efficiency of nutrient treatment, which include soil type and hydrogeologic setting, waste characteristics and load, indoor water use, recent meteorological conditions, separation and setback distance, system density, presence of riparian buffers, system type and size, presence and thickness of biomat, greywater, garbage disposals, system age, system maintenance, and system malfunctions. ***Malfunctioning OWSs are especially problematic since treatment can be "short-circuited" causing partially treated wastewater to discharge directly into groundwater and surface water.***

Past studies have estimated malfunction rates to be <7 – 20% in the US, with some communities experiencing up to 70% malfunction rates. More research is needed to evaluate how malfunctioning OWSs affect nutrient loading to water resources and how these nutrient inputs can be better managed. Denitrifying bioreactors are one such strategy that have potential to be effective attenuators of OWS-derived nutrients. Past studies have shown these strategies can reduce nitrogen concentrations from OWS and agricultural sources, especially if nitrate is the dominant nitrogen species. Partnering denitrifying bioreactors with phosphorus filters may allow for dual nitrogen and phosphorus treatment. Thus, more work evaluating the potential for denitrifying bioreactors to curtail nutrients from OWS is needed.

Evaluating the impact of on site wastewater systems in the Falls Lake watershed.

Key Research Questions

1. Do OWSs increase nutrient concentrations in and nutrient loads to streams draining to Falls Lake?

2. How do malfunctioning OWSs affect water quality in groundwater near the drainfield and streams located hydraulically downgradient from the drainfield?

3. Does the type of carbon source affect nitrogen treatment in bioreactors? Are denitrifying bioreactors a feasible nutrient management strategy for OWS in the Falls Lake Watershed?

Building bioreactors as part of the study.

Research Findings

Do OWSs increase nutrient concentrations in and nutrient loads to streams draining to Falls Lake?

Streams draining sub-watersheds served by OWSs contained elevated total dissolved nitrogen (TDN) relative to predominantly sewered sub-watersheds, whereas phosphate did not exhibit as clear of a trend. Stream phosphate concentrations in OWS sub-watersheds were elevated in the first year of study, but OWS sub-watersheds in the second year of study were similar to sub-watersheds served mostly by sewer.

Overall, the median TDN concentration in sub-watersheds served by OWSs contained a median of 1.58 mg/L, which was elevated relative to sewered sub-watersheds (median: 0.35 mg/L) and this difference was significant ($p< 0.01$). Two sub-watersheds (e.g., Passmore and Park Ridge) that were originally identified as OWS sub-watersheds were later determined by Wake County to have been converted to a community wastewater treatment system.

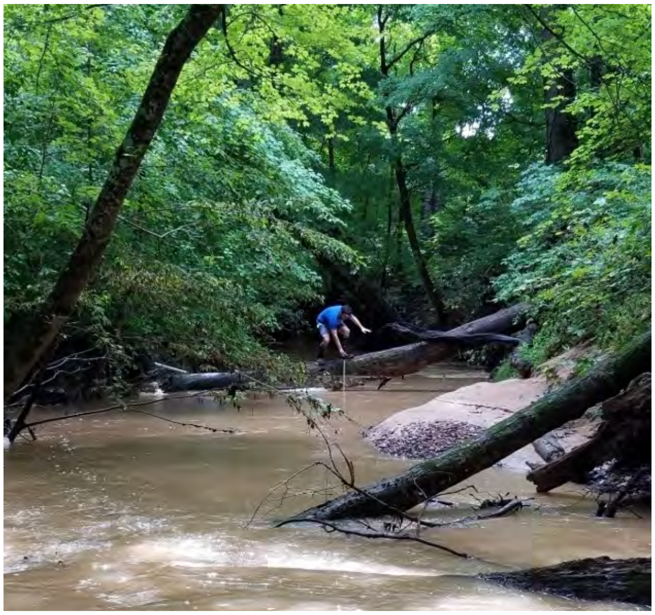
These sub-watersheds contained elevated TDN concentrations containing a median TDN of 17.53 and 9.16 mg/L for Passmore and Park Ridge, respectively. The elevated nutrients in streams draining these sub-watersheds presumably originated from legacy agricultural inputs. Aerial imagery indicates that land cover in the headwaters of these sub-watersheds was in agricultural production from 1993 up to approximately 2004 when the development of a residential subdivision began. Furthermore, due to the limited number of households, untreated wastewater is incapable of reaching these concentrations. Thus, legacy pollutants from agriculture are the most likely source of elevated stream TDN. Removing these sub-watersheds from the analysis altered the sewered median TDN to 0.14 mg/L. This trend was not observed in phosphate concentrations. The median stream phosphate concentration was 0.02 mg/L in sub-watersheds predominantly served by sewer and OWS. OWS sub-watersheds in the first year of study contained a median of 0.06 mg/L, whereas OWS sub-watersheds in the second year had a median of 0.01 mg/L.

This difference was due to the inclusion of a variety of sub-watersheds served by OWSs. When pooling nutrient data from OWS sub-watersheds included in both years of study, the median concentration of TDN and phosphate was 1.95 mg/L and 0.05 mg/L, respectively. In a follow-up study by O'Driscoll et al. [1], it was determined that sub-watersheds within the Triassic Basin of Falls Lake contained greater stream TDN and phosphate concentrations relative to sewered sub-watersheds during baseflow conditions. Thus, soil and geological characteristics also played an important role in nutrient leaching from OWSs to surface waters. ***These data suggest that OWSs have potential to increase stream nutrient concentrations by leaching nutrients into the shallow groundwater and a portion of these inputs translated to the local streams.***

Watersheds served by OWSs contained elevated TDN exports relative to sewered sub-watersheds. Overall, OWS watersheds across both years of study exported a median TDN mass of 0.78 kg-N/mo/ha. The first year of study contained a lower median mass export of 0.22 kg-N/mo/ha, whereas in the second year of study the median was 0.87 kg-N/mo/ha. When including Passmore and Park Ridge, the median mass export of TDN from sewered sub-watersheds was 0.21 kg-N/mo/ha, which was significantly different at $p< 0.01$. After excluding Passmore and Park Ridge, the median TDN export by sewered sub-watersheds was 0.05 kg-N/mo/ha.

Sub-watershed export of phosphate tended to be similar between OWS and sewered, except during the first year of study. During the first study, OWS sub-watersheds contained a median export of 30.4 g-P/mo/ha, but this was not significantly different from sewered sub-watersheds ($p = 0.58$). The median phosphate export from OWS sub-watersheds across both years of study was 4.9 g-P/mo/ha, which was slightly lower than the sewered sub-watersheds (6.69 g-P/mo/ha). This difference was insignificant ($p = 0.31$). Passmore and Park Ridge contained lower phosphate exports relative to the other sewered sub-watersheds; removing them increased the median phosphate export to 9.45 g-P/mo/ha, but phosphate exports remained insignificant ($p = 0.32$) between OWS and sewered sub-watersheds. There is a pond upstream of the sub-watershed outlet at Passmore, thus phosphate may be settling in the lake, but more analysis would be needed to confirm.

Results suggest that sub-watersheds served by OWSs contained elevated TDN exports compared to sewered sub-watersheds, whereas phosphate exports were similar. Thus, OWSs tended to be more efficient at treating phosphate relative to TDN, which was more mobile and more likely to leach into groundwater and eventually to surface water. Groundwater analysis in a follow-up study found that OWSs in the Falls Lake Watershed were more effective at treating phosphorus compared to nitrogen.



Gathering measurements.

Streams with greater concentrations of TDN and nitrate also tended to have elevated $\delta15N$ values. TDN concentrations and $\delta15N$ values exhibited a weak, positive correlation ($r = 0.33$) at $p = 0.01$. A moderately positive correlation ($r = 0.49$) was detected between nitrate and $\delta15N$ at $p < 0.01$. There is a gap in $\delta15N$ values from approximately 13 – 25‰, thus additional sampling when TDN and nitrate concentrations exceed 5 mg/L could improve the strength of this correlation. Past studies found that water resources recharged by OWS effluent tended to also contain elevated $\delta15N$ values [16, 17], especially in the 7 – 20‰ range. Of the 60 sub-watersheds analyzed for nitrate isotopes, most (80%) exceeded 7‰ and 83% of these were served by OWSs.

Sub-watersheds served by OWSs had a median $\delta15N$ value of 8.5‰ and the median concentration of TDN and nitrate was 1.81 and 0.69 mg/L, respectively, for sampling events where isotope fractionation occurred. Excluding Passmore and Park Ridge, sewered sub-watersheds had a lower median value of $\delta15N$ (6.99‰) and concentrations of TDN (1.25 mg/L) and nitrate (0.25 mg/L). Passmore and Park Ridge reported a median $\delta15N$ of 11.49‰, which corresponded with elevated median concentrations of TDN (7.94 mg/L) and nitrate (7.18 mg/L). More investigation is required to better understand the source of nitrogen and downstream impacts from these 2 sub-watersheds. Thus, streams with elevated TDN and nitrate concentrations coinciding with increased $\delta15N$ values may indicate OWS influences.

The full Fate and Transport of Nutrients from Onsite Wastewater Systems report can be found at: https://nutrients.web.unc.edu/

RESEARCH QUESTIONS

Two general themes of research were followed as part of our Falls Lake research studies: (1) vegetation-based pond retrofits and management and (2) stabilization of eroding urban channels by means of Stormwater Control Measures (SCMs).

RESEARCH METHODS

Floating treatment wetlands (FTWs) are employed to improve water quality in wet ponds but are often considered an expensive "add-on". We conducted a study to assess how strategic FTW placement might reduce costs while still yielding improved water quality treatment. FTWs were installed in a ring surrounding the outlet structure of an existing wet pond in Raleigh, NC (Armory Pond). Storm event-based water quality monitoring was conducted at the pond both pre- and post-retrofit to evaluate the FTW's impact on nutrients and sediment removal.

FINDINGS

During the pre-retrofit period, Armory Pond significantly reduced only NO2,3-N between the inlet and outlet. Post-retrofit, Armory Pond significantly reduced seven of nine pollutants analyzed, including total nitrogen (TN), total phosphorus (TP), and total suspended solids (TSS). Effluent concentrations were also significantly reduced from pre- to post-retrofit for organic nitrogen (1.13 mg/L versus 0.78 mg/L, respectively) and ammonia (NH3-N) (0.07 mg/L versus 0.04 mg/L, respectively). Vegetation monitoring revealed the greatest root lengths, biomass, and volumes were observed for Spartina patens (coastal cordgrass), Carex stricta (tussock sedge), and Juncus effusus (soft rush). Relatively high shoot: root biomass ratios (3 – 21) indicate annual harvesting of only shoots is an efficient method for providing permanent removal of nutrients from FTWs.

MANAGEMENT IMPLICATIONS

Overall, results suggest that strategic FTW placement can provide significant pollutant removal even at low surface coverage rates (i.e., <5%). As previous research in NC suggested 20% FTW coverage was needed to significantly improve water quality treatment, the lowered coverage recommendation may decrease the financial barrier to retrofit wet ponds and incentivize the use of FTWs in watersheds the state.

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Background

Stormwater retention ponds (also known as wet ponds) are a stormwater control measure (SCM) which could benefit from being modified (or retrofit) since they are one of the oldest and most common practices implemented in North Carolina (NC). Currently, the most common wet pond retrofit is the floating treatment wetland (FTW). FTWs are buoyant mats planted with wetland vegetation that rise and fall with changing water elevations. FTWs are a popular retrofit option for wet ponds that are underperforming as a result of their outdated or undersized designs. FTWs may also be considered in wet ponds located in nutrient sensitive watersheds (NSWs) such as the Falls Lake watershed to improve nutrient removal. Since the early 2000s, many studies have been conducted exploring the treatment mechanisms FTWs provide and their associated design components, though no universally accepted design standards have yet emerged from this research.

A common FTW design approach is to target a set surface coverage rate, wherein FTW mats cover a certain percentage of the waterbody's surface area. Relatively few studies have investigated the influence of FTW coverage ratio on water quality treatment, however, and those that did reported contrasting results. Alternatively, strategically placing FTWs within a wet pond to maximize runoff contact with the FTWs could yield more efficient water quality treatment. The goal of this study was to test the placement-based design strategy via a field-scale evaluation of FTWs installed in an existing wet pond in Raleigh, NC (Armory Pond). Water quality monitoring and FTW plant sampling were performed to quantify the impact of strategic FTW placement on storm event-based pollutant removal.

Research Methods

Beemats floating wetlands (Beemats, LLC, New Smyrna Beach, FL, USA) were installed at Armory Pond in July 2021. The FTW design was determined such that their placement would maximize runoff contact with the FTW root systems, prevent short-circuiting, and target runoff directly before it left the pond for final polishing. An octagonal ring of FTWs was thus installed surrounding the outlet structure at Armory Pond so that runoff entering the outlet from 360° would be forced through the FTWs before being discharged. In this way, the majority of treatment achieved by the pond would theoretically occur before runoff reaches the FTWs, which would then provide a final opportunity for gross filtration, nutrient uptake, and microbial removal. The FTWs were planted with a mixture of Juncus effusus (soft rush), Canna flaccida (golden canna), Carex stricta (tussock sedge), Iris virginica (blue flag iris), Pontederia cordata (pickerelweed), Spartina patens (saltmeadow cordgrass), and Paspalum vaginatum (seashore paspalum). The total FTW area was 33 m^2, which covered approximately 3.5% of the pond's surface area.

Storm event-based water quality monitoring was conducted at Armory Pond over two periods: a 5-month pre-retrofit period (February to July 2021) and a 10-month post-retrofit period (September 2021 to July 2022) (i.e., prior to and after FTW installation). Sampling stations were installed at three locations: (1) the closest major inlet catch basin, (2) the outlet catchment, and (3) a point immediately upstream of the FTWs (approximately 1 m) within the pond (herein called Armory inlet, outlet and midpoint, respectively). The inlet and outlet sampling stations were installed in October 2020, and the midpoint sampling station was installed in August 2021 to monitor water quality within the pond during the post-retrofit period only.

All sampling stations were equipped with ISCO 6712 automatic samplers which were programmed to pull 200 mL water aliquots at set intervals during storm events. Sample pacing intervals were set by either water flow rate or rainfall intensity. At the end of a storm event, samples at a given site were collected and analyzed for total suspended solids (TSS), ammonia-nitrogen (NH_3-N), Total Kjeldahl Nitrogen (TKN), nitrate + nitrite nitrogen ($NO_{2,3}$-N), total phosphorus (TP), ortho-phosphate (OP). Total nitrogen (TN), organic nitrogen (ON), and particulate-bound phosphorus (PBP) were then calculated from the analysis results.

FTW plants were also monitored to track root growth and plant uptake of pollutants via quarterly root length measurements and plant tissue analyses from November 2021 to May 2022. Three to six plants of each species present on the FTWs were randomly selected and removed from the FTW mats along with their aerator pots. Root lengths were determined by measuring the longest intact root from each plant from the base of the aerator pot. A subset of plants was then selected for laboratory tissue analysis. Plant shoots (above-mat tissues) and roots (below-mat tissues) were cut from the plants and placed in paper bags to make composite shoot and root samples. Composite plant plug samples representing the initial plant stock were also analyzed to provide a baseline comparison of shoot and root concentrations. All composite tissue samples were analyzed for nitrogen (N) and phosphorus (P) content (reported as mass percent).

Summary statistics were calculated using the water quality and rainfall data for each respective site and monitoring period. Storm-event-based water quality treatment was assessed by calculating the pollutant removal efficiency (RE) between the inlet and

Armory Pond FTWs; top row: aerial imagery depicting FTW design and water quality sampling locations (left) and FTW installation (right); bottom row: FTWs directly following installation (left), approximately 12 months following installation (center), and approximately 24 months following installation (right).

outlet sampling stations. The RE was calculated as the difference between the inlet and outlet event mean concentrations (EMCs). Paired influent and effluent concentration datasets from the respective monitoring periods were analyzed for statistical significance using paired t-tests (normally distributed data) or Wilcoxon signed rank tests (non-normally distributed data). Wilcoxon signed rank tests were then used to compare influent and effluent EMCs for the pre- and post-retrofit periods.

Results

The six and fourteen storm events were sampled during the pre- and post-retrofit periods, respectively, with average depths of 18.3 mm (0.72 in) and 20.1 mm (0.79 in), respectively. During the pre-retrofit period, Armory Pond effluent EMCs were the same or lower compared to respective influent EMCs on average, though only NO2,3-N was reduced significantly ($p = 0.036$). Mean pre-retrofit pollutant "removal" rates were negative for four of nine constituents (TKN, ON, PBP, and TP), indicating the pond was releasing higher concentrations of nutrients compared to what entered the pond. Pre-retrofit median REs were all positive except for in the case of PBP (-57%). The highest median pre-retrofit REs were achieved for NO2,3-N (70%), NH3-N (62%), and OP (71%). During the post-retrofit period, mean effluents EMCs were significantly lower compared to those from the influent for seven of nine pollutants, excluding PBP which had an average influent EMC of 0.11 mg/L and effluent EMC of 0.12 mg/L (essentially unchanged) and ON which was reduced but not to a significant degree. Median pollutant REs were positive for all nine pollutants, with the highest again achieved for NO2,3-N (83%), NH3-N (70%), and OP (79%).

Notably, median removal efficiencies improved for TN (52%), TP (46%), and TSS (45%) during the post-retrofit period compared to those from pre-retrofit (28%, 36%, and 16%, respectively). Moreover, median TN and TP effluent EMCs were reduced by approximately 25% each, and those for TSS were reduced by 43%. While post-retrofit inlet EMCs were typically higher than those pre-retrofit, no significant differences were found between the two influent datasets. Effluent EMC values were then compared for each pollutant, revealing that NH3-N and ON outlet concentrations were significantly lower during the post-retrofit period compared to those

J. E. Broyhill Park (Lenoir, NC) gully monitoring equipment with the rain gauges and autosampler on the left and the groundwater well and sample tubing on the right. Note the exposed sewer line in the right photo.

from pre-retrofit ($p = 0.046$). The remaining seven pollutants also had lower concentration, with the exception of OP. These reductions were not statistically significant, however, presumably due in part to limitations in the number of samples collected pre-retrofit.

Final FTW plant measurements revealed that Spartina, Juncus, and Iris accumulated the greatest shoot biomass while Spartina and Juncus had the greatest root biomass in terms of dry weights. Juncus also had the longest average root length (0.73 ± 0.11 m) as measured in May 2022, and both Juncus and Spartina had the greatest root volumes averaged between the May and August measurements (322 cm3 and 270 cm3, respectively). Plant tissue nitrogen concentrations ranged between 0.98 – 1.74% for shoots and between 0.89 – 2.46% for roots, while phosphorus concentrations ranged between 0.08 – 0.23% for shoots and between 0.18 – 0.28% for roots. While nutrient concentrations appeared relatively equal between shoots and roots in the baseline composite samples, root nitrogen concentrations generally increased over time while shoot nitrogen and phosphorus concentrations generally decreased over time. Still, shoots had an average biomass 7.5 times that of roots; therefore, harvesting of only shoots is recommended to maximize the efficiency of annual vegetation harvesting.

Conclusions, Management Implications, and Recommendations

This study was one of the first to evaluate the water quality treatment impact of strategic FTW placement near stormwater retention pond outlets. A noticeable improvement in water quality was observed between the pre- and post-retrofit periods, indicating that strategically placed FTWs can provide substantial improvements in wet pond pollutant removal even at low coverage rates (i.e., 3 – 5%). Based on these findings, we recommend installing FTWs such that they span the full width of a wet pond's flow path to maximize treatment.

Additionally, placing FTWs shortly upstream of a wet pond's outlet structure is recommended to provide final water quality polishing directly before stormwater is discharged to downstream waters. In this way, FTW treatment efficiency can be maximized, allowing lower coverage rates to achieve the same level of treatment as randomly placed FTWs. Decreasing the FTW coverage requirement can lower the cost to retrofit wet ponds and, in turn, increase the likelihood that more wet ponds are retrofit to improve water quality treatment in watersheds across the state, including nutrient-sensitive watersheds such as Falls Lake.

While the Armory Pond FTW design provided significant pollutant removal, more research is needed to confirm these findings due to the lack of pre-retrofit data collected. Future research is needed evaluating more FTW placement designs to determine the optimal arrangement of wetlands, including the distance from the outlet structure, number of FTWs, and whether wetland mats in series versus a single FTW mat should be used. Research findings will continue to inform FTW design recommendations and potentially lower the minimum coverage rate required to achieve significant water quality improvements, thus lowering the financial barrier on retrofitting stormwater ponds with FTWs.

The full Green Stormwater Infrastructure report can be found at: https://nutrients.web.unc.edu/

Policy in Focus: Community Engagement for Stormwater Decisions in Falls Lake

The rapid conveyance of urban stormwater through pipe networks, as is common in traditional systems, transports large volumes of untreated stormwater into receiving waters. These systems, therefore, threaten current environmental standards and the health and safety of downstream communities. Green infrastructure reduces and treats stormwater with measures including rain gardens, cisterns, green roofs, permeable pavers, bioswales, and wetlands. The effective and efficient implementation of green infrastructure in urban settings necessitates placing stormwater control measures on private property, and thus, requires significant community buy-in. This study investigates the impact of community engagement on the successful implementation of green infrastructure on private property.

In research led by Professor Danielle Spurlock of UNC-Chapel Hill, this project conducted 35 semi-structured remote interviews with elected officials, staff, nonprofit stakeholders, community residents, and developers to explore topics such as structure, frequency, type of community engagement projects, relationships with and between town agencies, and willingness to implement a range of stormwater management practices on private property in Granville, Person, and Wake Counties and Hillsborough (Orange Co.), Stem, Creedmoor, Butner, and Roxboro.

Key emergent themes from this study include:

1) persistent challenges arising from geographic location and size despite regional collaborative efforts.

2) Narrow problem definitions that artificially separate related topics.

3) Reliance on public awareness to motivate behavioral change.

Efforts to address the underlying root causes of larger tensions around development and capacity can help improve water quality and other regional development challenges. Participants discussed the creation of hierarchies where nuisance flooding and/or climate change took a backseat to nutrient loading. These interconnected issues resonate with community residents. Unfortunately, stormwater infrastructure investments did not fare well in cost-benefit analyses, which did not account for long-term cost savings or benefits that are difficult to monetize. Finally, current community engagement strategies emphasize increasing awareness but currently lack programming content to move residents toward action.

Regional collaborations must acknowledge power differentials in the structure and facilitation, and regional and state agencies can help address tension arising from limited resource availability. Programs that augment financial resources and further build capacity in rural and small jurisdictions may address multiple barriers to collective action to protect water quality. We also recommend programs focused on moving from awareness to action.

The above Policy in Focus is a summary of research conducted by UNC-Chapel Hill Professor Danielle Spurlock.

The full report can be found at: https://nutrients.web.unc.edu/

Appendix I

I

Legislative Text of Session Law 2016-94, Section 14.13. (c)

Of the funds appropriated to the Board of Governors of The University of North Carolina, the sum of five hundred thousand dollars ($500,000) for each of the fiscal years from 2016 – 2017 through 2021 – 2022 is allocated to the Chief Sustainability Officer at the University of North Carolina at Chapel Hill to designate an entity to oversee a continuing study and analysis of nutrient management strategies (including in situ strategies) and compilation of existing water quality data specifically in the context of Jordan Lake and Falls Lake.

As part of this study, the entity shall

(i) review data collected by the Department of Environmental Quality and by other stakeholders from water sampling in areas subject to the Falls Lake or Jordan Lake Water Supply Nutrient Strategies and compare trends in water quality to the implementation of the various elements of each of the Strategies and;

(ii) Examine the costs and benefits of basin wide nutrient strategies in other states and the impact (or lack of impact) those strategies have had on water quality.

The entity shall report to the Environmental Review Commission, the Environmental Management Commission, and the Department of Environmental Quality as set forth below:

(1) With respect to Jordan Lake, the final results of its study and recommendations for further action (including any statutory or regulatory changes necessary to implement the recommendations) no later than December 31, 2018, with interim updates no later than December 31, 2016, and December 31, 2017.

(2) With respect to Falls Lake, the final results of its study and recommendations for further action (including any statutory or regulatory changes necessary to implement the recommendations) no later than December 31, 2021, with interim updates no later than December 31, 2019, and December 31, 2020. No indirect or facilities and administrative costs shall be charged by the University against the funds allocated by this section. The Department of Environmental Quality shall provide all necessary data and staff assistance as requested by the entity for the duration of the study required by this subsection. The Department shall also designate from existing positions an employee to serve as liaison between the Department and the entity to facilitate communication and handle data requests for the duration of the project.

Appendix II

Roster of Falls Lake Study Team Members

Name	Affiliation
Piehler, Mike (Study Lead)	UNC-CH Institute for the Environment
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Collaboratory interns Alexia Civit, Anna Coley, Caroline Gravelle, Rose Houck, Auburn Robertson, and Emery Van Voorhis made significant contributions to the drafting of this report.

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