U.S. Fish and Wildlife Service/N.C. Wildlife Resources Commission Lake Mattamuskeet Technical Working Group (TWG) update, March 2022

Current Membership

Wendy Stanton, Refuge Fish and Wildlife Biologist, USFWS co-chair
Doug Howell, Migratory Game Bird Program Coordinator, NCWRC co-chair
Doug Newcomb, GIS Specialist, USFWS
John Stanton, Migratory Bird Project Leader, USFWS
Katy Potoka, District 1 Fisheries Biologist, NCWRC
Kevin Dockendorf, Coastal Fisheries Research Coordinator, NCWRC
Tom Augspurger, Deputy Field Supervisor and Ecologist/Environmental Contaminants Specialist, USFWS

Technical Expertise

Mike Wicker, Fisheries Biologist, Ecological Services, USFWS
Wilson Laney, (retired) Senior Biologist, Fisheries/Ecological Services, USFWS and Adjunct Assistant Professor, NCSU, Department of Applied Ecology

***Special thanks to Dr. Michelle Moorman and Dr. Adam Smith for water quality data management and analysis support and TWG members and other experts who have provided continued support and contributions including reviewing proposals and documents, sharing preliminary data/ results from graduate students and professors, data analysis, providing historical literature, communication, contracting and many other forms of support.**

Goal and Mission of TWG

As a collaborative TWG, we work together to identify, prioritize, and conduct monitoring and research at Mattamuskeet National Wildlife Refuge (NWR) to inform management actions that can be implemented to improve water quality and restore submerged aquatic vegetation (SAV) in Lake Mattamuskeet. The purpose of Mattamuskeet NWR is to protect and conserve migratory birds and other wildlife resources through the protection and management of wetlands. SAV is an important food source for waterfowl, and provides habitat for other migratory birds, and significant nursery and spawning habitat for fish and Blue Crabs. Refuge monitoring of SAV in Lake Mattamuskeet has occurred over the past 25 years. A noticeable decline in SAV in the west basin of the lake occurred almost two decades ago, while a sharp decline in SAV in the east basin of the lake has occurred over the past few years. From 2017 – 2019 and in 2021, no SAV was observed at sample plots during the refuge's annual survey. In 2020, refuge staff

observed muskgrass (*Chara* sp) at two plots with water depths at 1.1 to 1.3 ft (0.33 -0.39 meters) and secchi disk readings of 0.3 m (approximately 1 ft).

As a technical working group, we have been working to understand declines in SAV through the lens of a conceptual model published by Brinson and Davis (1980, Figure 1). This conceptual model has helped guide and develop recommended monitoring and research needs that we believe will help inform the management of Lake Mattamuskeet. The goal of providing recommended priority research and monitoring needs is to advance a science-based approach to improving water quality and restoring SAV in Lake Mattamuskeet through the implementation of best management practices identified in the approved Lake Mattamuskeet Watershed Restoration Plan and Addendum (2018, 2019).

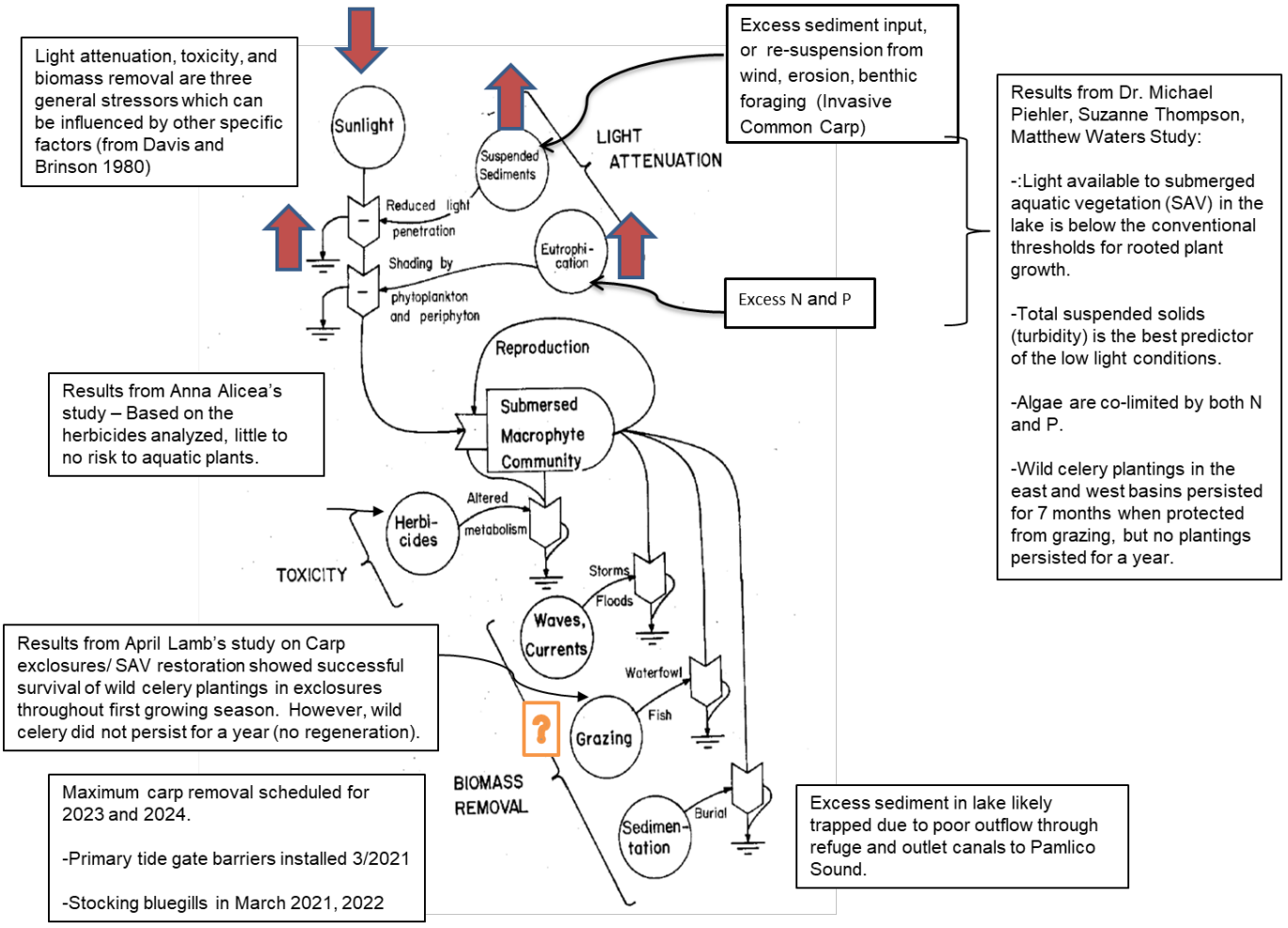

Figure 1. Model of submerged aquatic vegetation productivity (Davis and Brinson, 1980). Arrows indicate the trend of parameters that have been monitored and analyzed.

Monitoring, Research, and Planning Activities

Much of the literature on shallow-lake management suggests that SAV is one of the most important indicator species in shallow lakes. The SAV has declined and remained at 0% coverage for last 5 years at Lake Mattamuskeet (Figures 2 and 3). The alternative stable state theory for shallow lakes provides a synthesis of monitoring and management options needed when a lake flips from one dominated by clear water and aquatic plants to a turbid lake dominated by algae (Scheffer, 2004). The five components outlined for SAV restoration include 1) Monitoring, 2) Water Level Management, 3) Sediment Resuspension, 4) Nutrient Abatement, and 5) Fishery Management.

Monitoring (Water quality and SAV)

Monitoring is the systematic and purposeful observation and recording of activities taking place at Mattamuskeet NWR. It provides a pulse check on refuge health and includes activities such as bird surveys, fish surveys, vegetation surveys, and water-level and water-quality measurements. Monitoring of management outcomes is also being utilized to evaluate the effectiveness of a management action. Additionally, long-term monitoring datasets are essential to developing research questions and conducting research. Although monitoring requires resources, the TWG believes that monitoring programs need to be operationalized into Lake Mattamuskeet management and funds should be sought to support long-term monitoring of key parameters that guide lake management. Table 1 provides a provisional list of current and desired lake monitoring needs discussed by the TWG and the management actions they assess. All these monitoring activities are necessary because the information from the surveys will inform management response.

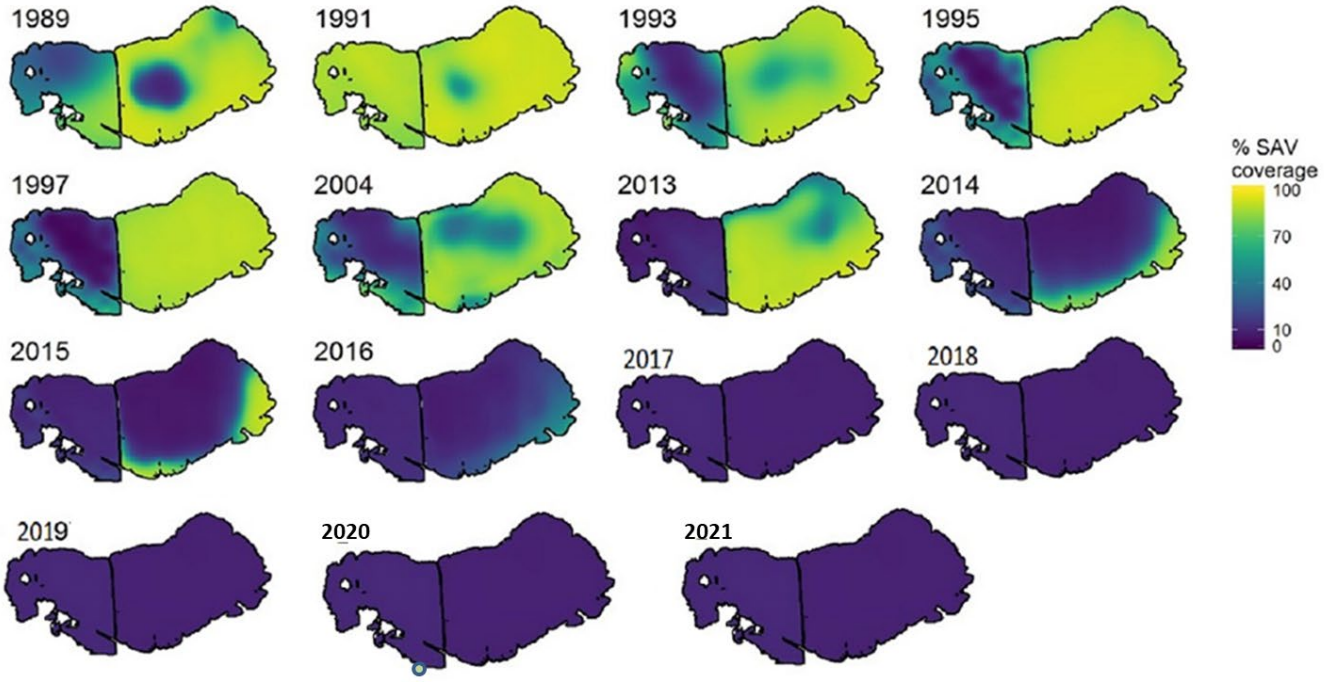

Figure 2. Estimated proportion of submerged aquatic vegetation (SAV) coverage from 1989-2021. During the annual SAV survey in 2020, we used a new application for mapping SAV (called SAV App). The dark green point on the southern side of the lake had an 80% presence of muskgrass (*Chara vulgaris*) in the plot. The water depth at the plot was 1.1 ft (0.33 meters) and secchi disk reading of 0.3 m (approximately 1 ft). A second point in that cove had less than 1% presence of muskgrass, water depth was 1.3 ft (0.39 m). These maps will not show traces of SAV less than 5% in a plot. During 2021, there was no SAV detected in the lake.

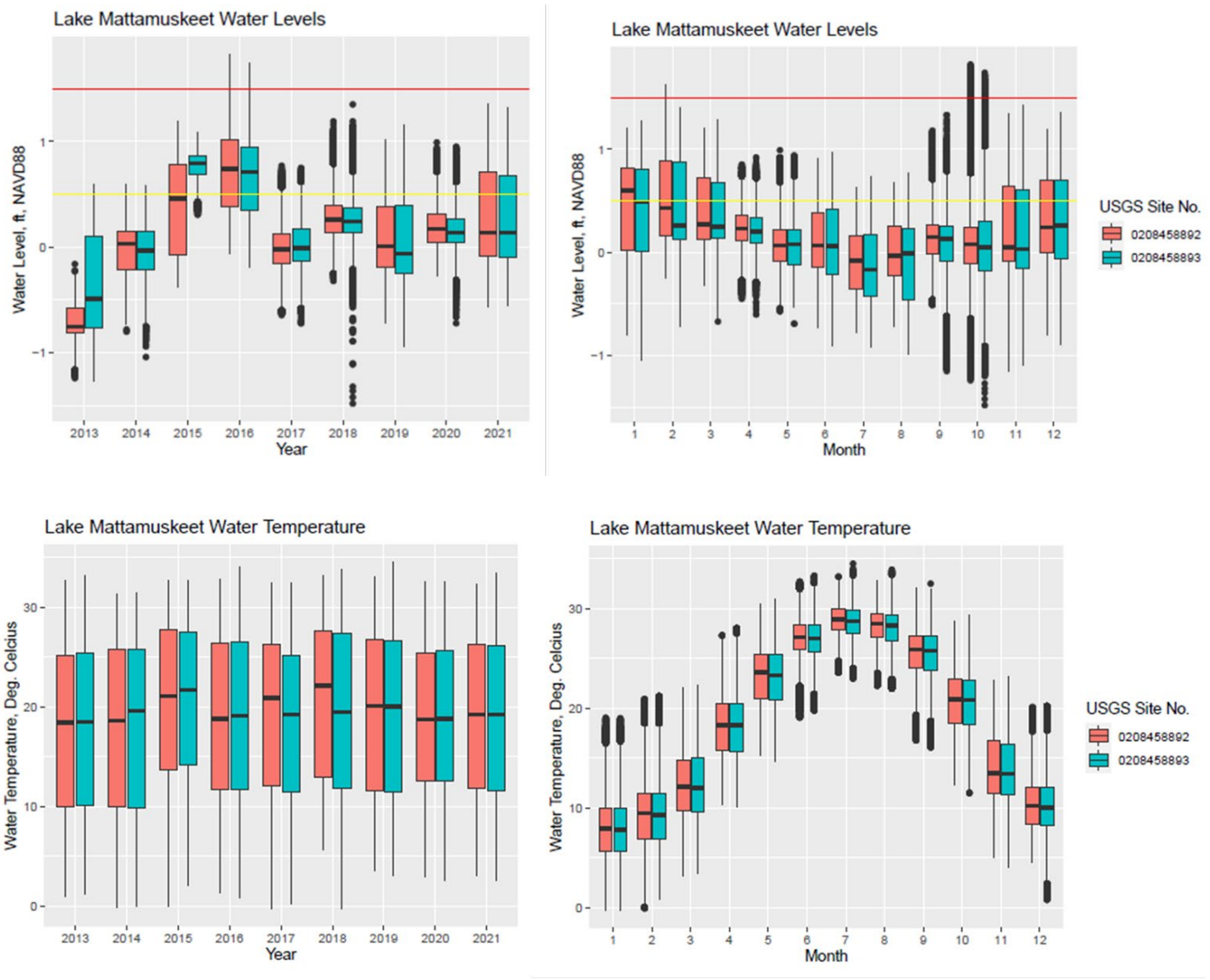

Figure 3. The top graphs show trends for mean maximum water levels for 2013 – 2021 annually and by month. The yellow lines represent gage heights for hot spot flooding and the red lines represent chronic flooding (identified by local stakeholders). The bottom graphs show trends in maximum water temperature for 2013 – 2021 annually and by month. The average coldest temperature was 7° Celsius or 45° Fahrenheit and the warmest average temperature was 39° Celsius or 82° Fahrenheit. The red columns represent the east basin and the green represent the west basin of the lake.

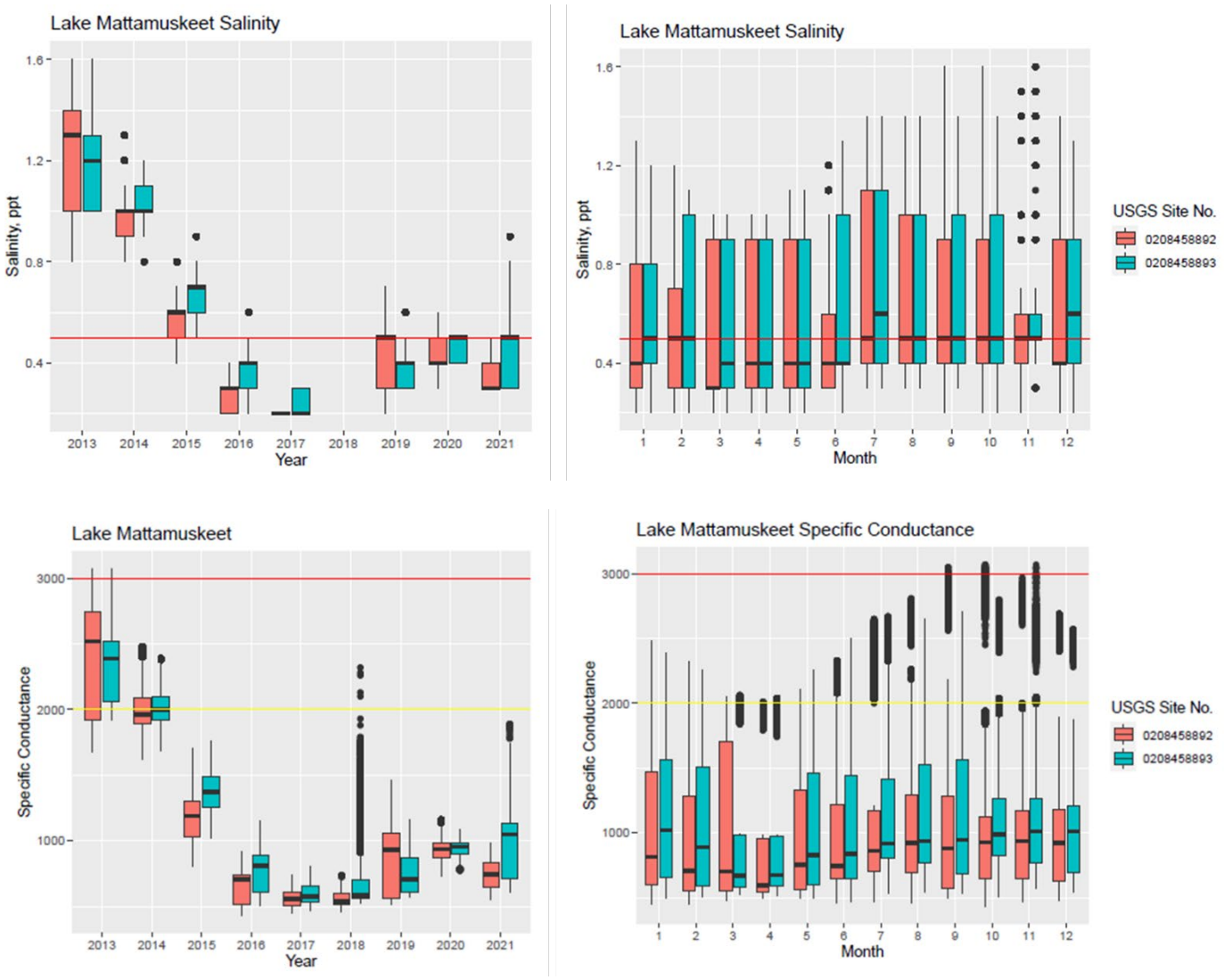

Figure 4. These graphs show trends in mean maximum salinity (ppt) and specific conductance by month and annually for 2013 – 2021. The red columns represent the east basin and the green represent the west basin of the lake.

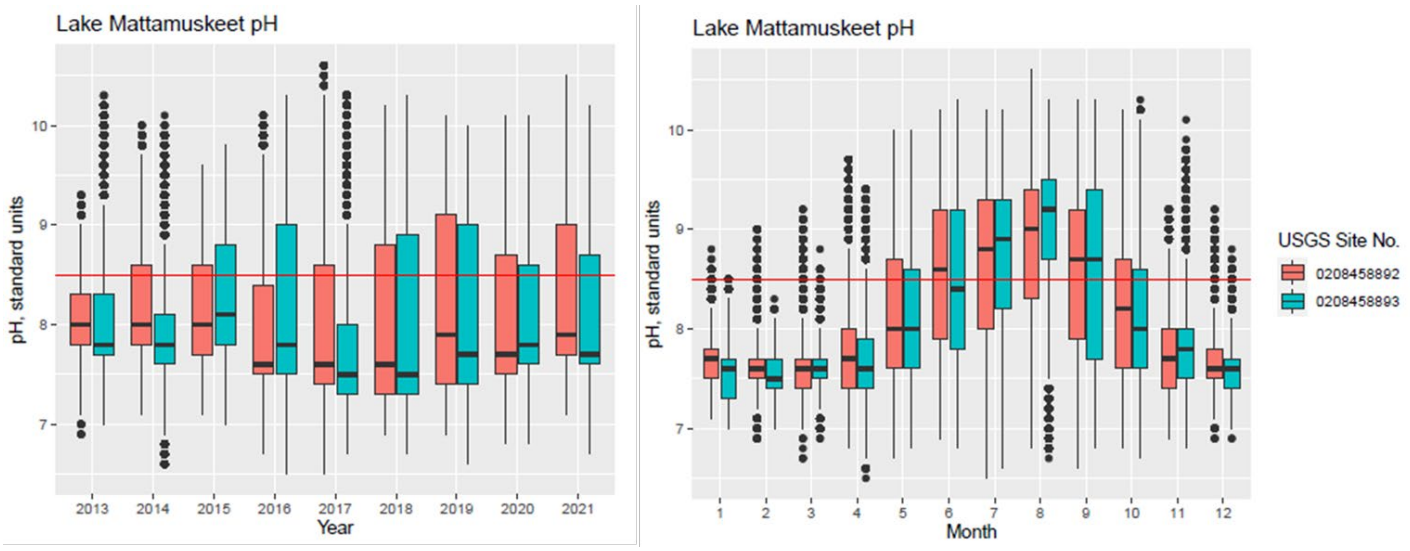

Figure 5. These graphs show trends in mean maximum pH by month and annually for 2013 – 2021. Red line is the threshold for waters NOT meeting state water quality standard of 8.5 and indicative of an algae bloom. The red columns represent the east basin and the green represent the west basin of the lake.

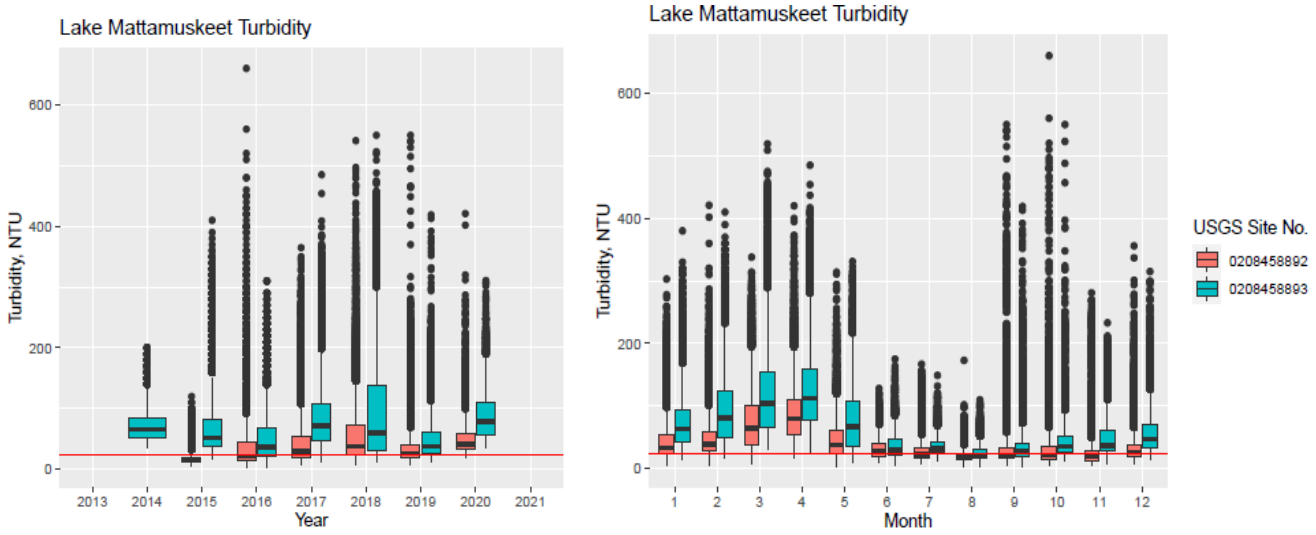

Figure 6. Exacerbated by common carp foraging behavior, these graphs show trends in mean maximum turbidity by month and annually for 2013 – 2020. Red line is the threshold for waters NOT meeting state water quality standard of 25 NTU. It should be noted that the sondes measure FNU which is similar but not NTU. Turbidity is highest in the spring which corresponds with the spring runoff events we see in the grab samples (influx of Nitrogen, Phosphorus and TSS). Wind events can also be higher in the spring which can affect turbulence. The red columns represent the east basin and the green represent the west basin of the lake. Due to mechanical, unreliability of the machinery (due to fouling and other issues) and calibration difficulties with the turbidity sensor, the turbidity parameter will no longer be measured at the USGS CWQ Station. Turbidity will be monitored by Secchi disk and monthly grab samples for total suspended solids collected between March – October.

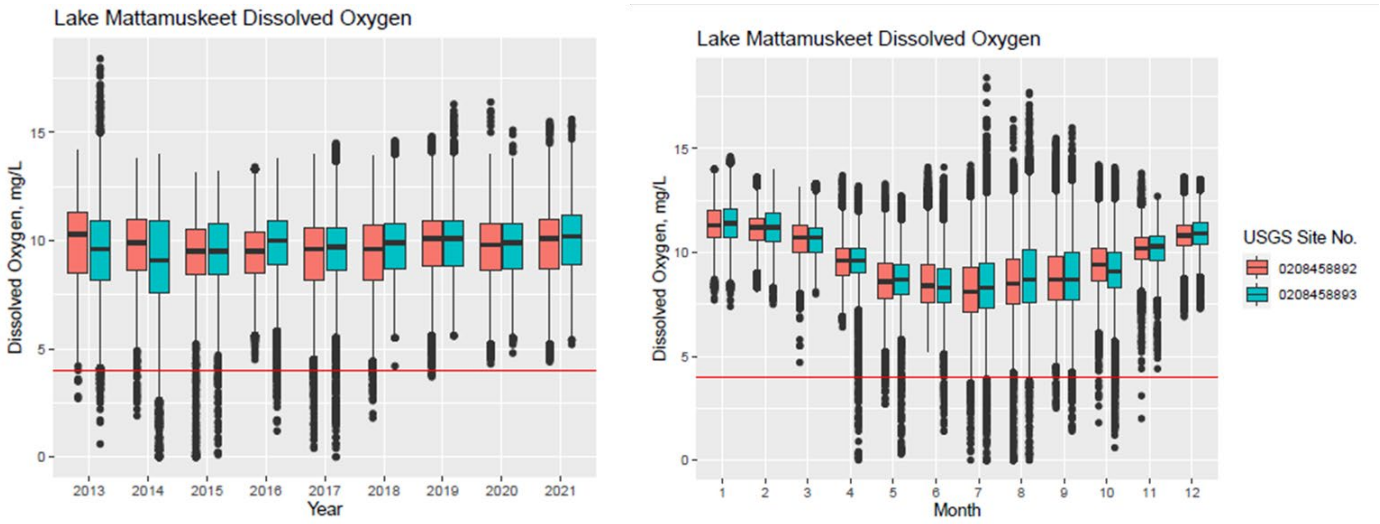

Figure 7. These graphs show trends in mean dissolved oxygen by month and annually for 2013 – 2021. Red line is the threshold for waters NOT meeting state water quality standard of <4. Low dissolved oxygen events in the lake are still relatively rare, likely due to the constant mixing from the wind events in the lake. The red columns represent the east basin and the green represent the west basin of the lake.

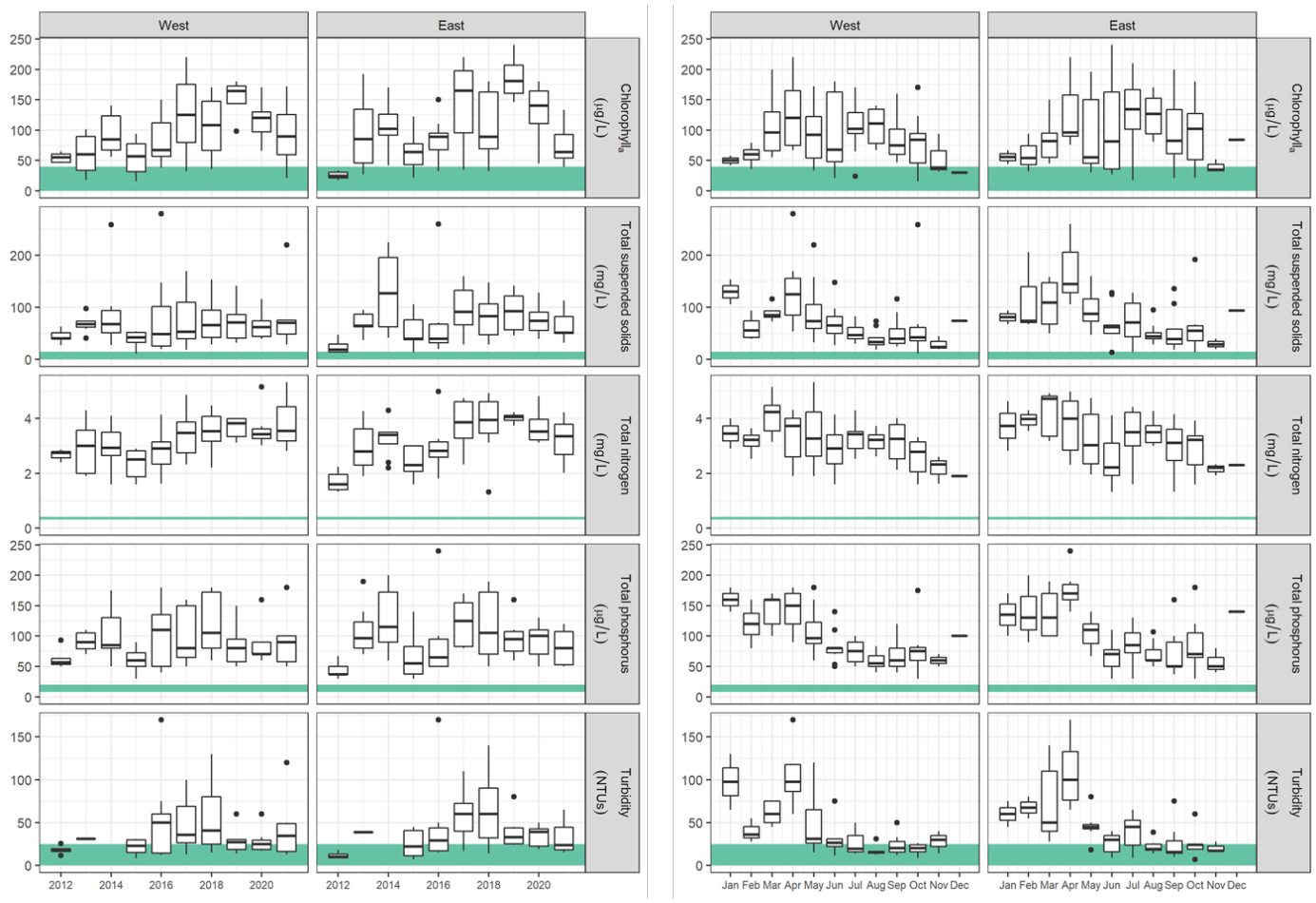

Figure 8. Annual and monthly boxplots of core parameters. The green lines show state or EPA standards for acceptable water quality.

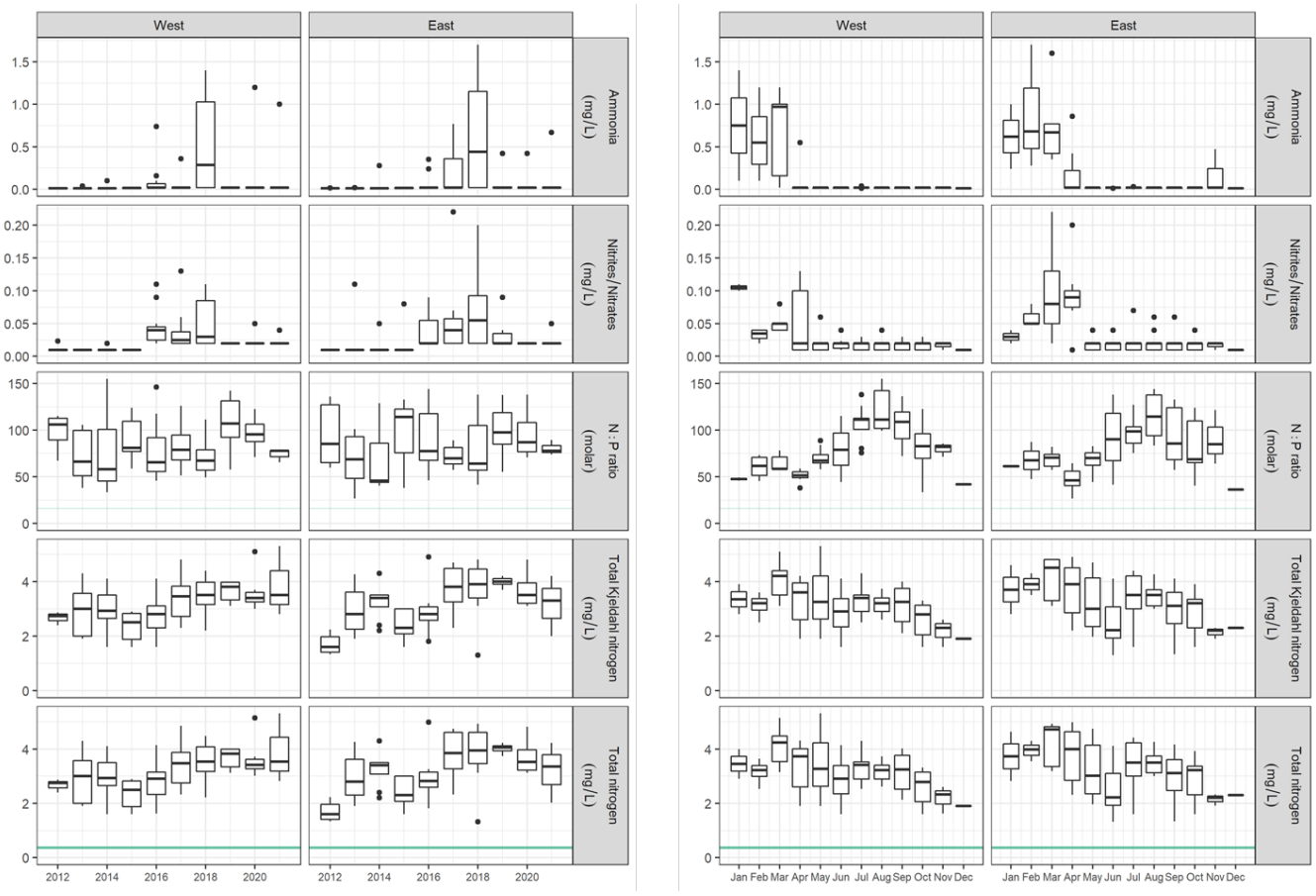

Figure 9. Annual and monthly boxplots of nitrogen parameters. The green lines show state or EPA standards for acceptable water quality.

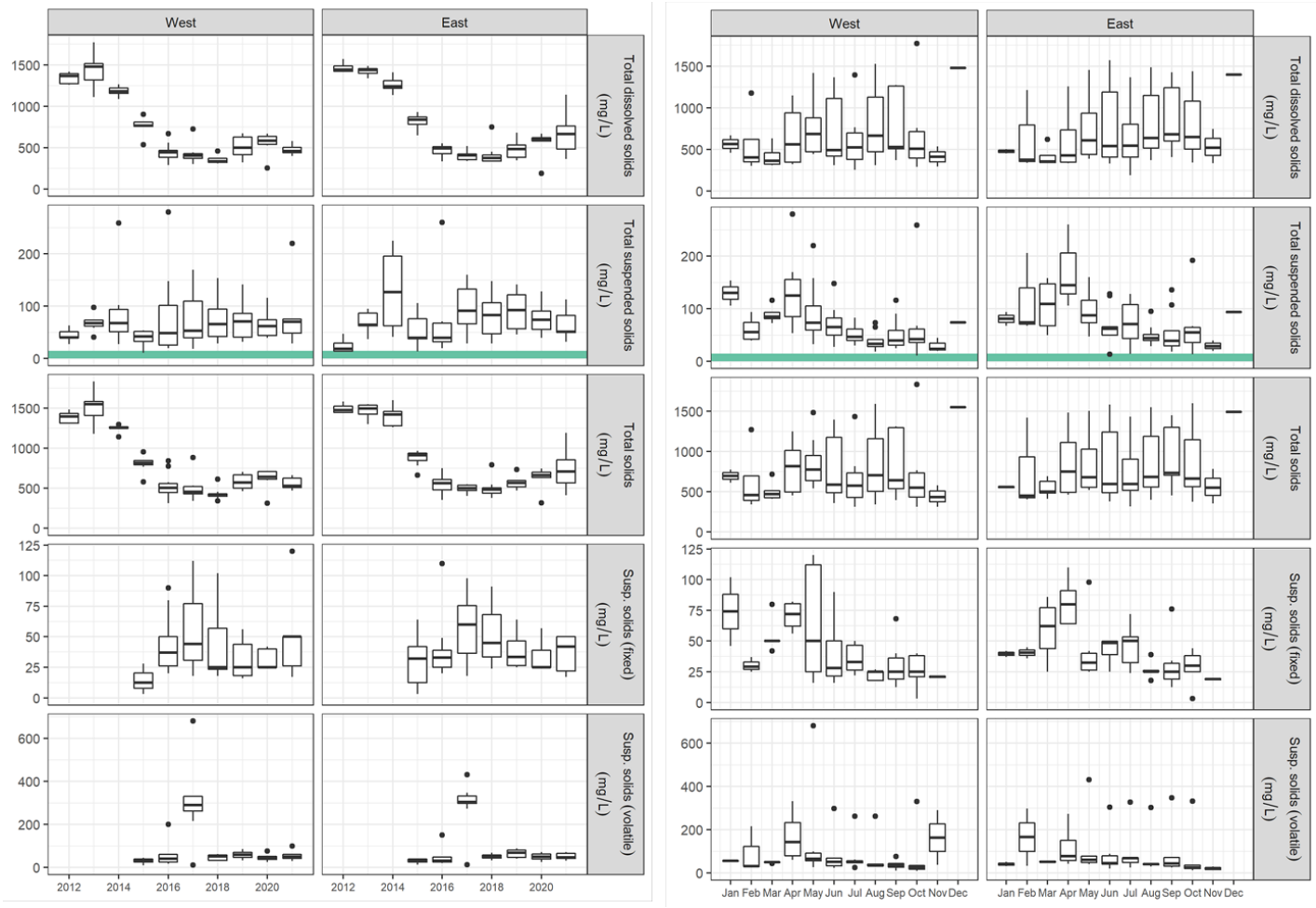

Figure 10. Annual and monthly boxplots of solids parameters. The green lines show state or EPA standards for acceptable water quality.

Table 1. List of current monitoring activities related to water quality and SAV management at Lake Mattamuskeet NWR.

Monitoring Activity	Frequency, Period of Record	How funded?	Justification/SAV management need	Comments
Continuous monitoring of lake levels and water-quality, precipitation, and wind speed	Continuous, September 2012 – 2021 ON-GOING	FWS, USGS, and NCWRC contributions, $411,600	Data required for watershed model, provides real-time data to assess lake hydrology and water quality, informs public on lake levels	USGS contracted to collect and maintain this data with in-kind assistance from FWS staff. Real time data available USGS CWQ site.
Real-time monitoring at Bell Island Pier (Pamlico Sound)	Continuous, September 2013 – present ON-GOING	USFWS as part of refuge operations and I&M program, $27,595	Provides information on water levels in the estuary which could affect outflows	Accomplished in coordination with FWS, I&M program, NCSU, and NC Emergency Management (NC FIMAN)
Monitoring of water levels, and water-quality in refuge canals	Weekly to monthly, 1977 – 2006, 2013 – present ON-GOING	USFWS as part of refuge operations	Gives an assessment of outflows, ensures gates are properly functioning, monitors saltwater intrusion	Data could be improved with instrumentation that provided for real-time monitoring of outflows

Table 1 (cont.). List of current monitoring activities related to water quality and SAV management at Lake Mattamuskeet NWR.

Monitoring Activity	Frequency, Period of Record	How funded?	Justification/SAV management need	Comments
SAV Monitoring	Annually starting in 2013 with occasional surveys dating back to 1989 ON-GOING	USFWS, part of refuge and FWS migratory game bird program operations	Monitors SAV occurrence and health, our primary indicator of ecosystem health for the lake	See updated SAV maps (Figure 2)
Monitoring of inland fish communities in Lake Mattamuskeet and associated refuge canals*	Annually ON-GOING	NCWRC, part of NCWRC operations	Provides an annual assessment of fish community structure in Lake Mattamuskeet and associated refuge canals	Provides justification for NCWRC game and nongame fish regulations in Inland Fishing Waters.
Aerial waterfowl surveys of lake	Annually, 1986 – present ON-GOING	USFWS, part of refuge operations; NCWRC, part of annual mid-winter waterfowl survey (Tundra Swans only)	Provides an annual estimate of waterfowl numbers at Lake Mattamuskeet	Tundra swans are an indicator species

***Note: In addition, there have been numerous fishery studies at Mattamuskeet NWR through the years that monitored individual species for varying periods of time (e.g. Harold**

Tyus's research on Alewife run into the lake; Randy Geddings's research on Striped Bass in the lake, ECU studies on fish passage by Dr. Roger Rulifson graduate students, and many others.)

Table 1 (cont.). List of current monitoring activities related to water quality and SAV management at Lake Mattamuskeet NWR.

Monitoring Activity	Needed Frequency	How funded?	Justification/SAV management need	Comments
Osprey productivity surveys	Annually, 1988-98, 2001-2004, 2013 – 2019 2020 -Present: Every 3-5 years ON-GOING	In-house, part of refuge operations	Provides an annual assessment of osprey nesting success and productivity	Osprey productivity has decreased in other locations as a result of poor water clarity
Lake water-quality monitoring – grab samples for nutrients, sediment, phytoplankton, and cyanotoxins	Annually during the growing season, 2012 – present; once every 5-10 years, ON-GOING	Variable, see comments	Monitors lake health, specifically related to recreational ecological health	Nutrient and sediment samples analyzed by NC DWR, Phytoplankton and cyanotoxin analysis is more variable and has been funded by a variety of special studies
Lake Mattamuskeet Angler Survey	Every 10 years (most recent completed in 2014)	Operational budgets (NCWRC and USFWS partner to leverage resources)	Angler preferences in catch and harvest; insight on angler demographics	Blue crabs, Black Crappie, and Channel Catfish comprised majority of angler harvest. Largemouth Bass and Common carp are also harvested by anglers

Research

Research for the TWG's purpose is the systematic investigation into and study of a system and its components in order to establish facts and reach new conclusions. Based on our current understanding of lake ecology and the Lake Mattamuskeet system we are prioritizing research that advances our understanding of why SAV is declining within the framework of the SAV conceptual model and what management strategies can improve our chances for SAV restoration. As an added benefit, much of this research will also advance our understanding of hydrology within the Lake Mattamuskeet watershed. Additionally, we believe that all TWG-associated research should be applied and solution oriented, i.e. the research will not only address the impact of the stressor being assessed, but it will provide probable solutions in the form of recommended interventions available to restore SAV through management actions.

Below is a list of our research priorities by topic followed by our justifications for these ranked research priorities. Table 3 summarizes the current research proposals we have with their respective ranks, principal investigator(s), costs, and comments. As a technical working group, it is our responsibility to review and rank proposals and work with investigators to make proposals more competitive and ensure their objectives meet Lake Mattamuskeet management needs.

Research Priority 1: Build a hydrologic and water quality model for the lake

A model is being finalized to produce a framework for further monitoring and research efforts by

a. providing a mathematical structure for understanding water levels and water quality in the lake

b. provide structure for data synthesis

c. facilitate predictions including efficacy of interventions to restore SAV

d. allows a sensitivity analysis to prioritize the management value of additional research

Research Priority 2: Further our understanding of sources of nutrients and sediment in the lake and their management

Trend analysis, SAV thresholds, and state water-quality standards all indicate recommended standards and guidelines have been exceeded for chlorophyll *a,* nutrients, suspended sediment, and water clarity so understanding all sources of sediment and nutrients and their magnitudes is critical. Sources of nutrients and sediment include in-lake recycling, inputs from the

landscape (run-off and pumping), atmospheric deposition, and groundwater. Furthering our understanding of these processes will identify which sources of nutrients and sediment are driving declines in water clarity and the potential efficacy of various strategies designed to reduce nutrients and sediments in the lake.

Research Priority 3: Understand impacts of biomass removal and/or bottom disturbance

Based on our SAV model, impacts of SAV biomass removal from waves, grazing and sedimentation can all reduce SAV. Furthering our understanding of these processes can inform the efficacy of management solutions, such as removal of fish (e.g carp) that reduce SAV biomass or add to lake turbidity, sediment removal during a period of low lake levels, and restoration of aquatic vegetation.

Research Priority 4: Understand the volume and quality of water leaving the lake (nutrient and sediment load)

Improving our understanding of lake outputs through the four canals that connect Lake Mattamuskeet to Pamlico Sound improve our understanding of lake residence time as well as how various climatic and water level scenarios in the lake and sound impact lake hydrology. The water quality component lets us determine the extent of nutrients leaving the lake to complete the modeling of nutrient inputs, in-lake stores, and outputs.

Management Activities

Carp Removal Project

Accomplishments:

- During 2020, the TWG and Carp Team were awarded two grants for carp removal: The Coastal Fund Program grant (received FY 2020) for $180,000, and the USFWS Large Invasive Species Grant (will receive FY 2023) for $1,000,000.

- In 2020, with the Coastal Funds Program Grant, the Refuge's friends group, Coastal Wildlife Refuge Society, contracted with a local welder to retrofit the existing debris barriers (now called Carp Barriers) with flat metal bars at two inch spacing (Figure 12) to prevent adult carp from entering the lake from the Pamlico Sound. To assist with reducing the floating debris accumulation on the lake side of the barriers, the barriers could be lifted to allow debris to pass through the tide gates. **However, there were two significant concerns with the original barrier design. First, the barriers are difficult to lift, resulting in safety concerns when the water pressure increases against the barriers during high flow events. Secondly, when the barriers are lifted, there is increased risk of new carp entering the lake. Carp are attracted to water flow and can**

aggressively swim through water and debris through the tide gates when the barriers are lifted.

- In 2021, due to difficulty raising the barriers during high water flow events, four of the barriers (one for each tide gate) were cut in half to assist with floating debris removal (Figure 12). The upper half of the gate can be easily lifted to allow passage of floating debris. In addition, a boom was tested and installed at the Rose Bay Canal and has effectively directed floating debris towards the modified barrier (Figure 13). However, when the floating debris trapped by the boom remains for extended periods of time, it becomes saturated and will sink below the boom and potentially reduce drainage capacity at the tide gate.

Figure 11. At least one carp barrier at each tide gate (4 total) have been cut in half to reduce the weight of lifting during high water flows for debris passage. The lower half of the gate remains in place and the upper half is lifted.

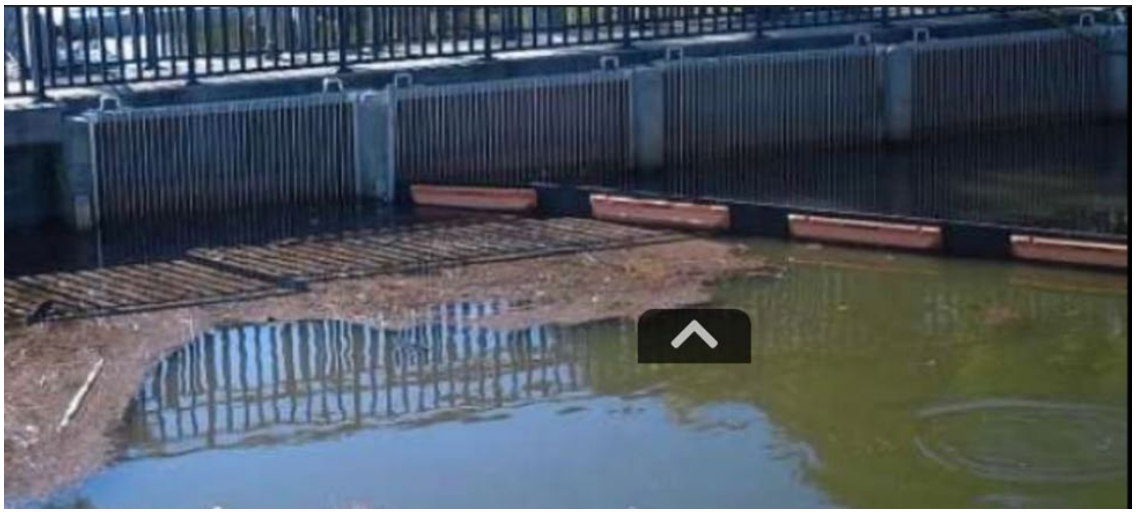

Figure 12. A 25-foot boom was installed across the Rose Bay Canal to direct floating debris towards the modified barrier. The upper half of the barrier is lifted and the debris can flush through tide gate.

- Carp barriers are effectively blocking incoming adult carp from the Pamlico Sound into the Lake. New signs were installed at the four tide gates to explain the importance of carp removal for aquatic grass (SAV) restoration in the lake (Figure 14).

Figure 13. New signs installed at the four tide gates explain the importance of the carp barriers for SAV restoration. In addition, occasionally dead carp are observed on sound side of the barriers and is proof they are working to block new carp from entering the lake.

- The final Environmental Assessment (FONSI- finding of no significant impact) and Compatibility Determination for maximum carp removal was open for public comments on March 29 – April 29, 2021 and finalized in August 2021.

- March 2021, 78,000 Bluegills were stocked along the southern perimeter of the lake. Bluegills are voracious predators on carp larvae and eggs (Figure 15).

Figure 14. The North Carolina Wildlife Resources Commission raised and stocked bluegills in the lake to assist with carp management strategies (bluegills eat carp eggs).

Current and ongoing projects:

- The TWG is collaborating with East Carolina University on two ECU Capstone Project teams to assist with carp removal priorities. One team is designing recommendations for the required secondary barrier and biosecurity for the outlet canals. The biosecurity component will address protection during storm surge events and a secondary barrier to block carp if the primary barrier is damaged or compromised during debris removal. The second team is designing recommendations for deterrent devices and barriers. The deterrent device will be used to scatter carp away from the tide gate when barriers are

lifted for debris removal. The deterrent barriers will be placed around the five Highway 94 culverts and other strategic locations around the lake to block carp.

- The TWG is continuing to work with the USFWS contracting specialists about contracts for carp removal.
- The TWG is coordinating with NCDOT to complete an encroachment permit to install deterrent devices around the 5 Highway 94 culverts.
- The NCWRC stocked 200,000 bluegills during March 2022.
- The USFWS staff will conduct further investigations into potential recruitment of carp from Refuge waterfowl impoundments, and control methods.

Future projects:

- Install secondary barriers and biosecurity requirements for storm surge evens in the four outlet canals.
- Conduct the maximum carp removal during 2023 – 2024.

Table 2. List of completed research activities related to water quality and SAV management at Lake Mattamuskeet NWR, 2012-2020. More than $698,000 in research and graduate and undergraduate students have been supported through state, federal, and academic partnerships. As the final reports are received, they are archived and can be accessed here (ServCat reference 102865)

Project Title & Investigator	Funding	Project Completion Date	Realized Outcome: Project application to lake and/or watershed management and restoration
Sibel Ozen and Dr. Stacy Nelson (NCSU Thesis), *Using historic remotely-sensed data to monitor changes in light attenuation at Lake Mattamuskeet*	Completed as part of a NCSU graduate thesis, Funded by Country of Turkey	May, 2016	**Research Priority 2:** Project developed a water-clarity model for Lake Mattamuskeet from LANDSAT 8 data.
Scott Winton (Duke Dissertation), *Monitoring of methane and nutrient production in Refuge impoundments*	Funded through Duke Graduate program	May 2016	**Research Priority 1:** Develop an initial nutrient source assessment for Lake Mattamuskeet.
Dr. Dan Obenour and Brianne Walker (NCSU undergrad project), *Hydrologic modeling to improve management practices at Lake Mattamuskeet*	Funded through NCSU undergraduate research grant, $4,000	August 2016	**Research Priority 1:** Developed a lake routing model for Lake Mattamuskeet in R.
Michelle C. Moorman, Tom Augspurger, John D. Stanton, and Adam Smith (*2017*) Where's the Grass? Disappearing Submerged Aquatic Vegetation and Declining Water Quality in Lake Mattamuskeet. Journal of Fish and Wildlife Management: December 2017, Vol. 8, No. 2, pp. 401-417.	Funded through USFWS, staff time provided	December 2016	**Research Priority 2:** Assesses trends in SAV and water-quality through time. This information informs our understanding of why SAV have declined and is the basis for why management actions are needed. A popular article was published in Wildlife in North Carolina and published in the Dec 2017 issue of J. of Fish and Wildlife Management. The final article can be found here.
Dr. Celeste Journey and Barry Rosen (USGS pub in review), *Assessment of toxic cyanobacteria occurrence in Lake Mattamuskeet, to protect wildlife and recreational users.*	Funded through USFWS I&M grant, $18,330	December 2016	**Research Priority 2:** Assesses phytoplankton communities and cyanotoxin production on a seasonal basis at Lake Mattamuskeet.

Continued Table 2. List of completed research activities related to water quality and SAV management at Lake Mattamuskeet NWR, 2012-2020. More than $698,000 in research and graduate and undergraduate students have been supported through state, federal, and academic partnerships. As the final reports are received, they are archived and can be accessed here (ServCat reference 102865)

Project Title & Investigator	Funding	Project Completion Date	Realized Outcome: Project application to lake and/or watershed management and restoration
Lindsey Shanks (Montclair State University Thesis), *Targeting SAV Restoration at Lake Mattamuskeet Using GIS and Landsat 8 Data*	Funded through Montclair State University and DFP, $7,000	May 2017	**Research Priority 1&2:** Develop a habitat suitability model for SAV based on water clarity, water depth, and the presence of SAV to target areas for restoration.
Michelle Moorman, *Assessment of toxic cyanobacteria occurrence in the food chain at Lake Mattamuskeet*	Funded through a USFWS Wildlife Health Grant	December 2018	**Research Priority 2:** Determined risk of cyanotoxins to recreational users and consumers at Lake Mattamuskeet. Final report completed (ServCat Reference 102868).
Dr. Randall Etheridge (ECU), *Participatory mapping of surface water hydrology as an initial step in the restoration of Lake Mattamuskeet.*	Funded by USFWS regional office, $9,674	Spring 2018	**Research Priority 1**: The project will start to develop a watershed map and flow paths for the lake based on community input. Additionally, it will solicit input from landowners in the Mattamuskeet watershed on problems and solutions related to Lake Mattamuskeet.
Dr. Randall Etheridge (ECU), *Reducing flooding and improving water quality in Lake Mattamuskeet*	Funded as an ECU capstone project, $11,000	Spring, 2018	**Research Priority 1 and 4:** Project mapped the bathymetry of the four outfall canals leaving the lake and developed a HEC-RAS model to help determine the current restrictions to flow in the canals and what the potential impact of sea level rise will be on flow out of the canals.
Dr. Celeste Journey (USGS), *Baseline information to determine pesticide occurrence and concentrations in Lake Mattamuskeet*	Funded in FY17 through I&M RFP process, $14,880	December 2018	**Research Priority 5:** Collect pilot information on the potential concentrations of pesticides in the lake in various locations including the mouth of agricultural drainage ditches.
Dr. Mike Piehler, *Assessing the potential for ecosystem enhancement on Lake Mattamuskeet.*	Funded through NCWRC (Pittman-Robertson; Federal 75%; State 25%), $232,815	December 2020	**Research Priorities 1, 2, and 3**: This included conducting both lake and canal assessments, SAV transplant experiments, phytoplankton bioassays which helped determine which nutrients might be limiting, and flux experiments to help provide info on in-lake contributions of nutrients for the purpose of guiding SAV restoration

Continued Table 2. List of completed research activities related to water quality and SAV management at Lake Mattamuskeet NWR, 2012-2020. More than $698,000 in research and graduate and undergraduate students have been supported through state, federal, and academic partnerships. As the final reports are received, they are archived and can be accessed here (ServCat reference 102865)

Project Title & Investigator	Funding	Project Completion Date	Realized Outcome: Project application to lake and/or watershed management and restoration
Dr. Randall Etheridge (ECU), *Assessment and modeling of strategies to reduce the impact of waterfowl impoundments on the eutrophication of Lake Mattamuskeet.*	Funded through ECU start-up money, $231,575, **Additional funding from NSF grant received!**	2019	**Research Priority 2:** Project will enhance start-up research being conducted at ECU starting spring 2016. The research will quantify field scale measurements of sediment and nutrients in the predominant landscapes draining to the lake (agricultural, impoundments – both agricultural and native emergent marsh impoundments). The proposed model will test the efficacy of various water management strategies.
Dr. Raymond Smith and Mr. Mike Borer (ECU), CapStone Project with undergraduate engineering students to design a Carp Exclosure Gate Hoist System	$3,000 (USFWS) plus inkind from ECU (professor and student expertise)	December 2020	**Research Priority 3: Understand impacts of biomass removal.** Project will assist with Carp removal by designing and constructing a hoist system to lift Carp Exclosure gates located at the 4 outfall canals.
April Lamb and Dr. Jesse Fisher (NCSU, now USGS) with WRC, *Identify seasonal Common Carp (Cyprinus carpio) aggregations, investigate removal techniques, establish baseline population characteristics, movement, and behavior to identify and assess the feasibility of targeted management strategies for ecological restoration*	Funded through NSF Master's research project ($156,353 plus $5,000 from FWS)	June 2020	**Research Priority 3:** This proposal will address approaches designed to guide the responsible removal of carp in the lake and reduce sediment resuspension to enhance SAV abundance. Results showed wild celery growing inside the exclosures.
NCSU PhD study, Anna Aleisha and Dr. Greg Cope	Funded through NCSU graduate program (plus $5,000 for supplies FWS)	May 2020	**Research Priority 5:** Will complement USFWS baseline study of pesticides and help model pesticide loads to Lake Mattamuskeet. Anna defended her dissertation on March 20, 2020.

Continued Table 2. List of completed research activities related to water quality and SAV management at Lake Mattamuskeet NWR, 2012-2020. More than $698,000 in research and three graduate students have been supported through state, federal, and academic partnerships. The received final reports can be accessed here (ServCat reference 102865).

Project Title & Investigator	**Funding**	**Project Completion Date**	**Realized Outcome: Project application to lake and/or watershed management and restoration**
Dr. Raymond Smith (ECU), A Hydrologic Process Model for Lake mattamuskeet NWR	$45,254 USFWS I&M RFP	December 2022	**Research Priority 1:** Project will model hydrologic processes for the Lake. This model is being finalized. Youtube link to March 10, 2022 presentation: **https://youtu.be/wP_4d4eKCe8**
Kevin Dockendorf (NCWRC), *Identification of factors that may influence movements of Largemouth Bass between Lake Mattamuskeet and adjacent canal habitats*	NCWRC Sport Fish Restoration (Dingell-Johnson; Federal 75%, State 25%), $60,000 plus leveraging of available resources	December 2021	**Research Priority 3: Understand impacts of biomass removal.** Largemouth bass are a popular gamefish for anglers as well as an apex predator in the food chain at Lake Mattamuskeet. Understanding habitat use and movement during varying water levels is expected to provide insight for angling opportunities, recruitment success, and relationship to SAV habitat, and potential foraging behavior. Study completed October 2021. Report available: https://bit.ly/3L48LUI

Table 3. List of current research and engineering activities related to the implementation of the Lake Mattamuskeet Watershed Restoration Plan. Currently, over $560,000 in research is being funded through academic, state, and federal partnerships.

Project Title & Investigator	Current Funding Status	Anticipated Project Completion Date	Anticipated outcome of project application to lake and/or watershed management
USDA, Subaqueous soil survey of Lake Mattamuskeet	In-kind from USDA with in-kind contributions from USFWS	December 2019 – ongoing.	**Research Priority 2:** Project will assess suitability of lake sediments for SAV restoration. We have not received final report. Field work was delayed because of equipment issues.
UNC, *Tracking water storage in Lakes: Citizens and Satellites*	Funded through NASA Citizen Science for Earth Systems Program	Summer 2018 - present	**Research Priority 1:** Develop water level and inundation model for Lake Mattamuskeet based on remotely sensed data.
2019 Storm Recovery, Hyde County	Funded by the Office of State Budget and Management, ($1,800,000)	June 2021 extension requested)	Research Priority 2: Construction of a pump station and related watershed restoration infrastructure for the Lake Mattamuskeet watershed.
Drs. Randall Etheridge and Charlie Humphrey, Monitoring to determine *Enterococci* and fecal coliform concentrations during baseflow and storm events in Lake Mattamuskeet (Mattamuskeet NWR) and the Pamlico Sound (Swanquarter NWR)	Funded by FY2018 USFWS I&M Branch ($19,914)	December 2022	**Research Priority 2:** Further our understanding of sources of nutrients and sediment in the lake and their management

Continued Table 3. List of current research and engineering activities related to the implementation of the Lake Mattamuskeet Watershed Restoration Plan. Currently, over $560,000 in research is being funded through academic, state, and federal partnerships.

Project Title & Investigator	Current Funding Status	Anticipated Project Completion Date	Anticipated outcome of project application to lake and/or watershed management
Engineering Active Water Management within the Lake Mattamuskeet Watershed, Geosyntec Consultants	Funded to Hyde County through N.C. Clean Water Management Trust Fund ($158,000)	August 1, 2021	1. Watershed-Scale Hydrologic & Hydraulic Model 2. Wetland Siting and Capacity Analysis 3. Project Engineering Design 4. Consultation and Oversight
Using Undergraduate Engineers and Community Engagement to Build Resilient Coastal Communities, Dr. Randall Etheridge, Dr. Raymond Smith, Dr. Linda D'Anna, Dr. Cindy Grace-McCaskey, East Carolina University	Funded by National Science Foundation	June 2022	Investigate the feasibility of the following projects: 1. Canal Dredging 2. Pat Simmons' Property Sheet Flow 3. Mattamuskeet Association Sheet Flow
Two ECU Capstone Projects with undergraduate engineers to design and model biosecurity and secondary barriers for carp project and deterrent devices for carp project.	Funded by Coastal Funds Program and ECU	June 2022	The expectations include: 1) to design a gate with two inch spacing to block invasive carp from entering the lake from the outfall canals. This gate will serve as a secondary biosecurity barrier and allow easy maintenance for flushing or removing debris that will reduce water flow. 2) a portable or temporary deterrent system to scatter carp away from the tide gates when the carp gate lifted. 3) a permanent or semi-permanent carp deterrent system or device to block carp passage at strategic locations in the lake. 4) a power source to operate the portable and permanent deterrent systems.
2019 Storm Recovery, Hyde County	Funded by the Office of State Budget and Management, ($1,800,000)	June 2021 (extension requested)	Construction of a pump station and related watershed restoration infrastructure for the Lake Mattamuskeet watershed.

Table 4. List of proposed and currently unfunded research activities related to SAV management at Lake Mattamuskeet NWR.

Rank	Project Title & Investigator	Cost	How proposal will be applied to the SAV conceptual model and inform lake and/or watershed management
High Priority; Critical to Restoration Plan	Daniel Obenour, Ph.D., P.E.; Sankar Arumugam (NCSU), *Watershed and Water Quality modeling to Inform Lake Mattamuskeet Ecosystem Management*	$128,884	**Research Priority 1:** This proposal will provide a mathematical framework for understanding hydrology, water-quality, and SAV declines and restoration for the lake ecosystem where hypotheses can be tested. Initial work on the lake routing model was completed in summer of 2016.
High Priority; Critical to Restoration Plan	Dr. M. Piehler (UNC-IMS) and Dr. R. Etheridge, Quantifying surface-water loading of nutrients and suspended solids to Lake Mattamuskeet	$450,000	**Research Priorities 2 and 4:** Proposal will identify incoming loads of nutrients and suspended sediment to the lake and identify strategies for reducing these loads.
Not Ranked; secondary priority	Dr. D.R. Corbett and J.P. Walsh (ECU), *Evaluating the Role of Material resuspension and trapping in water quality dynamics of Lake Mattamuskeet*	$301,756	**Research Priority 2:** This proposal will determine the role of in-lake sediment and nutrient cycling in Lake Mattamuskeet and how these processes impact water clarity and quality.

Planning and Management Activities

As Lake water quality/SAV restoration progresses, monitoring and research information will be used to adaptively inform future lake planning and management activities as part of the lake/water quality restoration. In addition, all management actions will be tracked and monitored.

Table 5. List of planning activities related to SAV restoration at Lake Mattamuskeet NWR.

Title	Current Funding Status	Anticipated Project Completion Date	How plan will guide management for SAV and water-quality restoration at Lake Mattamuskeet
NC Coastal Federation, *Nine Element Plan for Lake Mattamuskeet*	Funded jointly by USFWS, NCWRC, and Hyde County, $80,000	Fall, 2018 Addendum 2019 completed and approved by NCDWQ	Plan provides a blueprint, best management practices and strategies to improve water quality in Lake Mattamuskeet and improve hydrology in the Lake Mattamuskeet Watershed
USFWS Habitat Management Plan	Developed by USFWS	December 2017	Plan will provide guidance on overall habitat management at Mattamuskeet NWR and guide Refuge operations.
USFWS Water Resource Inventory and Assessment	Funded through USFWS, $5,000	December 2021 (In progress)	Assessment will synthesize known information regarding Refuge hydrology and water quality
Public comment period for EA and CD for carp removal	N/A	March 29-April 29, 2021	This is required compliance documentation that must be completed before moving forward with carp removal.
*Carp Removal	Funded through USFWS: $180,000, $1,000,000	2021-2024	A massive Common Carp removal will improve water clarity in the lake as validated by April Lamb's preliminary results and historic carp removal success in the lake conducted in the 1940s – 1960.