Emmons & Olivier Resources, Inc.
for the Comfort Lake Forest Lake Watershed District

Forest Lake In-Lake Management Feasibility Study

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water
ecology
community

Cover Image

EOR Biologists Jimmy Marty and Mike Majeski Collecting Sediment Cores

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Executive Summary

A 2018 Diagnostic Study and Implementation Plan Update identified that a Total Phosphorus reduction of 923 lbs./year was needed at Forest Lake to achieve a long-term, five-year average summer phosphorus concentration at or below 30 ppb as identified in the Comfort Lake Forest Lake Watershed District (CLFLWD) 2022-2031 Watershed Management Plan. Since 2018, the CLFLWD has achieved over 80% of the external load reduction goal for Forest Lake. However, as past studies have indicated, there is still an internal reservoir of phosphorus in Forest Lake that continues to hinder the improvement of water quality in the Lake.

Due to its shape, Forest Lake can be identified as having three basins: West, Middle, and East (Figure 1). A description of each basin's characteristics is provided in Chapter 2 of this document. Water quality data collected from 1984-2021 shows that surface water phosphorus and chlorophyll-a concentrations are improving on the West Basin. However, surface water phosphorus and chlorophyll-a concentrations have been declining on both the Middle Basin and Eastern Basin (Table 1).

Table 1. Forest Lake Water Quality Trends

Forest Lake Basin	Total Phosphorus	Chlorophyll-a	Secchi Disk
West	Improving since 1984 **Significantly Improving since 2012**	**Significantly Improving since 2001**	Improving since 1984 **Significantly Improving since 2012**
Middle	*Declining since 2012*	*Declining since 2012*	Improving since 2012
East	*Declining since 2012*	*Declining since 2012*	**Significantly Improving since 2012**

Further, both the Middle Basin and East Basin are deep lakes, susceptible to strong thermal stratification and anoxic bottom water during summers. A review of dissolved oxygen profile data suggests both basins experience anoxia occurring for at least 90 days/year at depths greater than 15 feet, which suggests internal loading of phosphorous from the lakebed is likely an important source of phosphorus to both basins.

While no threshold of external phosphorus reduction has been identified to trigger the use of internal load measures (MPCA, 2020), a review of water quality trends provides evidence to suggest that the external load reductions achieved to date have not resulted in a significant reduction of in-lake total phosphorus concentrations in the Middle and East Basin. Summertime spikes in phosphorus and chlorophyll-a concentrations are still noted annually on these basins. These spikes are correlated with algae blooms and perceived poor water quality. On the Middle Basin and East Basin, these seasonal trends are heavily correlated with loads from internal sources including loads from the release of phosphorus from the sediment in areas of the lake that go anoxic during the summer. The purpose of this study is to evaluate the feasibility of in-lake management practices to achieve management goals.

In December 2021, the CLFLWD Board authorized further investigations to address internal phosphorus loads impacting Forest Lake. The interconnected lake dynamics necessitated looking at the interactions of inactivating phosphorus release from bottom sediments, carp, and appropriate native aquatic plant re-establishment. Improving the water quality of Forest Lake will require management of all three.

This Forest Lake In-Lake Feasibility Study identifies several potential sediment phosphorous management options most applicable to Forest Lake, including:

- **Phosphorus Cycling**
    - In-Lake Alum Treatment
    - Hypolimnetic aeration
    - Sediment dredging
- **Vegetation Management**
    - Continued management of invasive aquatic plants using targeted herbicide treatments
    - Create and maintain a dynamic (living) vegetation management plan
- **Carp Management**
    - Focused Population Survey
    - Harvest/Exclusion
    - Fish Stocking

These options were investigated in further detail which includes an examination of the ecological and recreational benefits, challenges, and cost-benefit of each option. Analyses completed as part of this study included:

a) Analysis of 11 lake sediment cores by Professor Bill James at the University of Wisconsin-Stout Center for Limnological Research and Rehabilitation; and,
b) Review of current and historic fisheries surveys (carp population numbers) and aquatic vegetation surveys to determine appropriate fish and aquatic plant management techniques.
c) Review water quality and aquatic plant survey data from lakes where alum has been applied.

We identified the following combined approach of three management activities at this time to be the most practical and cost-effective way to address internal phosphorus loading to Forest Lake:

1. **In-Lake Alum Treatment:** Conduct an alum treatment of the Middle Basin. We recommend splitting the total alum dosage into two separate applications. The initial dosing of the Middle Basin would occur in Summer/Fall of 2023 and the second one in the Summer/Fall 2025. Consistent with the District's Adaptive Management philosophy, delaying the second dosing until 2025 would allow for the ability to assess the effectiveness of the first treatment and design the second treatment (if needed) in a more accurate, cost-effective way. An alum treatment of the West Basin and East basin is not recommended at this time.

2. **Vegetation Management:**

    a. Continued baseline management of curly-leaf pondweed (CLP) and continue to conduct aquatic plant surveys to minimize expansion of invasives and allow natives to establish in shallow areas using targeted herbicide.

    b. Create and maintain a dynamic (living) vegetation management plan that seeks to continuously evaluate and incorporate the latest aquatic plant management practices. The Forest Lake Vegetation Management Plan (FLVMP) will build upon the annual pre-treatment and post-treatment survey work already being completed by Blue Water Science. Further, the LVMP will explore the positive and negative aspects of various aquatic plant management techniques and establish lake specific aquatic plant management goals that are in line with the District's 2021 AIS Prevention and Management Plan.

3. **Carp Management:**
    a. Conduct a focused population survey to validate carp populations remain below 30 lb./acre. The fishery survey should include a population assessment of adjacent wetlands and streams that may provide additional spawning habitat.
    b. Maintain carp abundance below 30 lb./acre by identifying opportunities to prevent carp from migrating to adjacent waterbodies.
    c. Maintaining a healthy native fish community should organically prevent carp from exceeding the 30 lb./acre threshold.

Management activities with associated timing and costs are presented in Table 2 below. The ultimate goal behind the implementation of the proposed management activities in Forest Lake is to generate the internal load reductions needed to achieve a long-term, five-year average summer phosphorus concentration at or below 30 ppb as identified in the CLFLWD 2022-2031 Watershed Management Plan. Rather than focusing on a targeted hypolimnion phosphorus concentration, the focus should be on the practices that will reduce sediment phosphorus release rates in both the anoxic and oxic portions of each basin.

These management activities should be undertaken iteratively using an adaptive management approach.

Table 2. Recommended Management Plan Activities

Management Activity	2023		2024		2025	2026	2027
	Fall '22 - Spring '23	Summer Fall	Fall '23 - Spring '24	Summer Fall			
Alum treatments (Middle Basin)[1]		**$280,000**			**$310,000**		
Baseline invasive plant management[2]		**$35,000**		**$37,000**	**$40,000**	**$43,000**	**$25,000**
Create/ Maintain a Lake Vegetation Management Plan		**$15,000**			**$5,000**		**$5,000**
Conduct focused fisheries survey to validate carp populations		**$10,000**					**$6,000**
Total	**$0**	**$340,000**	**$0**	**$37,000**	**$355,000**	**$43,000**	**$36,000**
						Grand Total	**$811,000**

[1] Two alum doses at $280,000 and $310,000 each. A range of costs for the alum dosing application materials and labor are shown in Table 2. Costs are based on a cost of $1.93 per gallon of alum applied (Personal Communication, John Holz). The costs presented do not include administration, design, permitting, or other management costs.

[2] Cost represents treatment of CLP up to 120 acres (specific area size to be determined annually) and includes Blue Water Science Surveys

1. INTRODUCTION

The purpose of this report is to **1)** identify an in-lake management plan for reducing internal phosphorus loading from bottom sediments to Forest Lake; and **2)** identify a proactive strategy for maintaining a healthy littoral zone that sustains water quality, is resilient to future Aquatic Invasive Species (AIS) infestations, and supports aquatic recreation. The report consists of a detailed overview of the recommended in-lake management plan with a 5-year schedule and annual costs, followed by individual sections discussing each in-lake phosphorus management option identified as most applicable to Forest Lake.

Existing data was compiled to assist with analyzing in-lake treatment options. Lake water quality sampling data through June 2022 as well as carp surveying data were provided by CLFLWD. Aquatic vegetation data from the ongoing annual point intercept surveys conducted by Blue Water Science provided insights into the current distribution and density of aquatic vegetation. Of principal importance for evaluating internal phosphorus loading and the cost feasibility of alum treatments in Forest Lake was core sampling and laboratory analysis of the lake bottom sediments. The morphometry of Forest Lake is unique in that it contains both deep basins (Middle, East) and shallow basins (West) (Figure 1). Section 2 of this report provides background information on how the morphometry of each basin impacts internal loading.

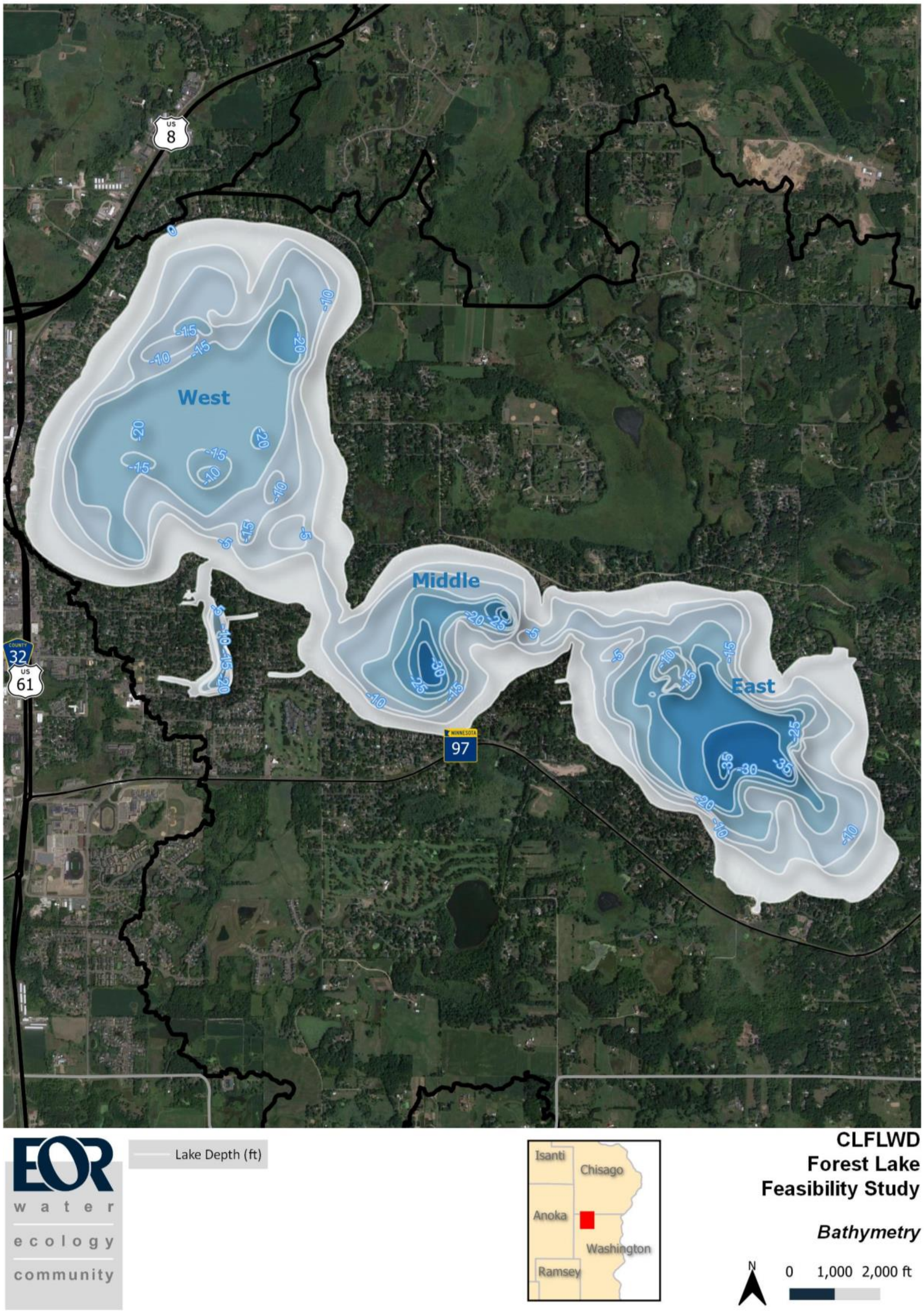


Figure 1. Forest Lake bathymetry.

2. BASIN CHARACTERISTICS

2.1. Middle Basin

The Middle Basin has a maximum depth of 30 feet and a mean depth of about 14 feet. A review of in-lake data collected on the Middle Basin from 2019-2021 showed a consistent pattern with high hypolimnion phosphorus concentrations from June through September prior to an October mixing (turnover) event. Furthermore, dissolved oxygen (D.O.) and temperature data showed that the basin was stratified from June until early September in both 2020 and 2021. Therefore, phosphorus release was possible from early June until early September in both years, with increasingly high phosphorus levels occurring in the hypolimnion by August prior to a fall turnover (mixing event).

2.2. Eastern Basin

The Eastern Basin of Forest Lake has a maximum depth of 35 feet and a mean depth of 12.6 feet. Observed growing season phosphorus concentrations were below the 40 µg/L State standard in both 2019 and 2020. Fifteen (15) of the 16 hypolimnion samples collected from 2019-2020 were also below 40 µg/L. One sample, collected in August of 2020 had a phosphorus concentration of 50 µg/L. D.O. monitoring conducted in 2019 and 2020 suggested the basin was stratified from mid-June until early September in both years. Therefore, phosphorus release was possible from mid-June through early September. However, bottom phosphorus concentrations remained low.

2.3. Western Basin

The Western Basin of Forest Lake has a maximum depth of 22 feet and a mean depth of 9.9 feet. Observed growing season phosphorus concentrations were below the 40 µg/L standard in both 2019 and 2020. Similarly, eighteen (18) of the 19 hypolimnion samples collected from 2019-2020 were below the 40 µg/L standard. D.O. monitoring conducted in the 2019 and 2020 suggested there was no extended period of low oxygen in the bottom waters. The Western Basin is likely intermittently stratified during periods of the year and may be subject to multiple mixing events throughout the growing season.

3. PHOSPHORUS CYCLING MANAGEMENT

3.1. Mapping Treatment Area

A weight of evidence approach (Figure 2) was employed to map alum dosing rates and treatment areas within each basin. The final alum dose and treatment area was determined based on lake bathymetry, sediment core Releasable Phosphorous (RP) content, biobase bottom hardness measurements, Hypolimnion/Epilimnion water quality sampling results, and an update to the Forest Lake BATHTUB lake response model (Section 3.4 [Lake Response Modeling Update]).

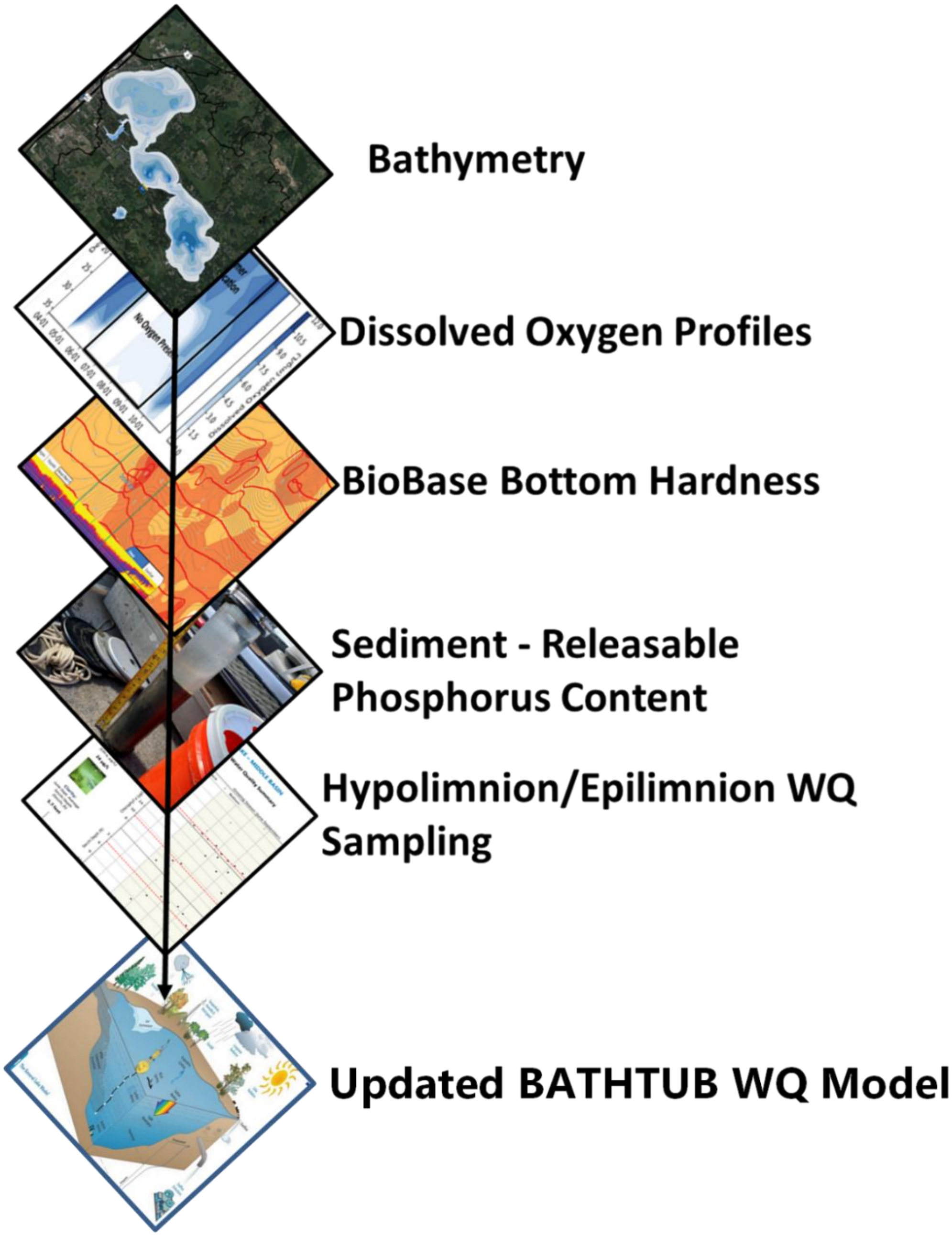


Figure 2. GIS inputs (weight of evidence) used to develop targeted alum dosing treatment plan.

3.2. Sediment Characteristics, Coring Analysis, & Results

3.2.1. Bottom Hardness

Identifying area of the lake with sandy or gravel sediments is an important factor in identifying areas with low phosphorus release rates. While data has not been collected throughout Forest Lake, a comparison of bottom hardness data from BioBase's social map identified "hard" bands of sandier or perhaps gravel/rock sediment (dark orange/red areas), within the Western Basin of Forest Lake (Figure 3). This information, when combined with results from the sediment core analysis (Section 3.2.2 [Sediment Core Analysis]) provided additional evidence to suggest that an alum treatment may not be needed in the West Basin at this point.

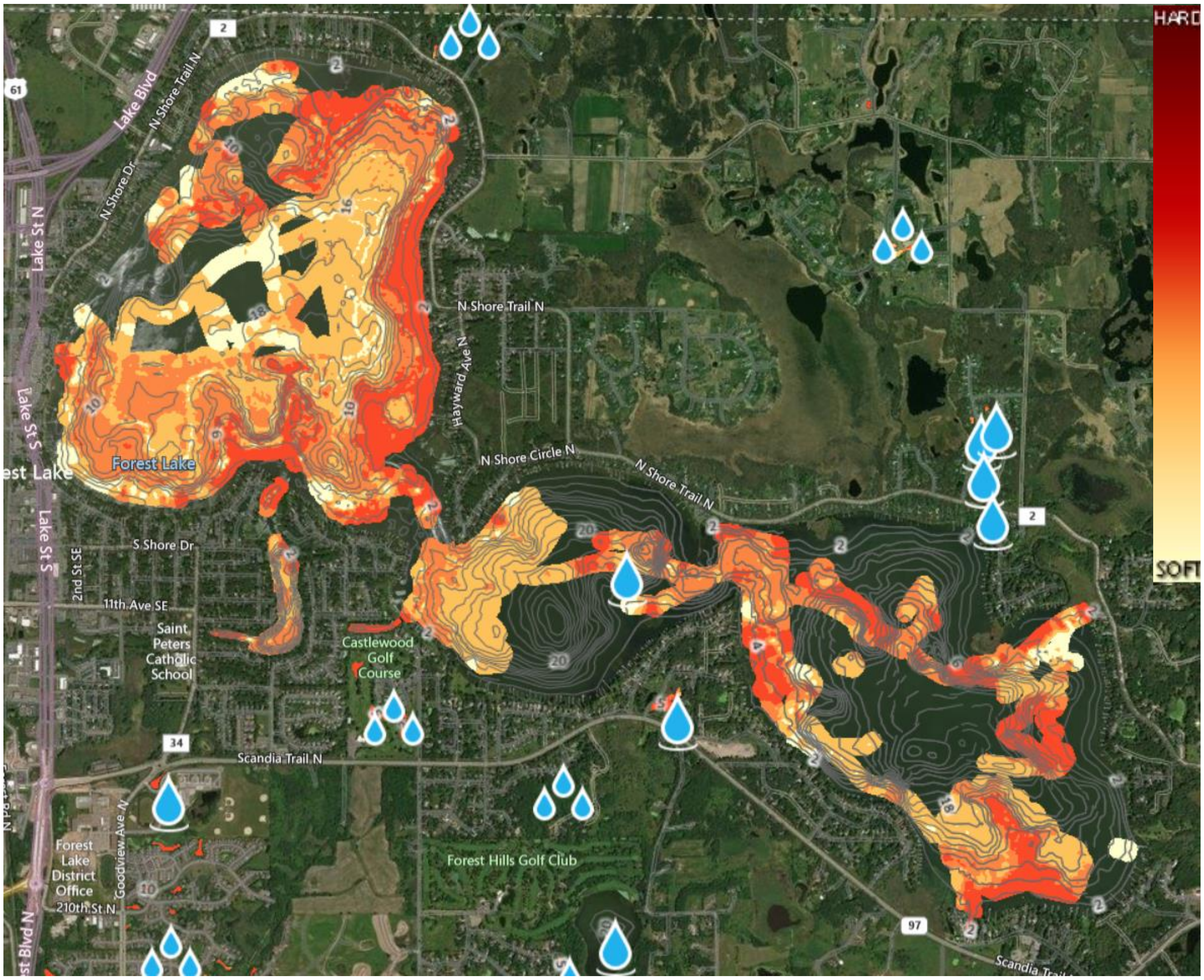


Figure 3. Forest Lake BioBase bottom hardness estimates. Blue water drops represent locations where sonar data has been voluntarily contributed by C-Map Genesis (Biobase) users.

3.2.2. Sediment Core Analysis

Nine (9) sediment cores were collected by EOR staff on March 18, 2022 including two (2) cores from the West Basin, four (4) cores from the Middle Basin, and three (3) cores from the East Basin (Figure 6). Two (2) additional cores, including one (1) from the East Basin, and one (1) from the Middle Basin were collected on May 29, 2022. The 2 additional cores were used to validate a decrease in Redox-Sensitive Phosphorus (RP) concentrations below the first 6 cm in the sediment.

Each core section was analyzed by the University of Wisconsin-Stout Center for Limnological Research and Rehabilitation for sediment total phosphorus and phosphorus fractions. Sediment cores were sectioned in 2-cm increments to a sediment depth of 12 cm. Statistical analyses were performed to identify the presence or absence of trends in RP content based on sediment depth within the sediment core (0-2 cm, 2-4 cm, 4-6 cm, and 6-12 cm).

Analysis of the sediment cores was required to achieve the following three objectives:

1) Determine the pool of RP in the lake sediments that is available to migrate into the overlying water column.
2) Measure the release rate of sediment phosphorus.
3) Determine the amount of alum required to inactivate sediment phosphorus and reduce internal phosphorous loading.

3.2.3. Using Lake Bathymetry/Dissolved Oxygen Profiles to Inform Sediment Core Location

A review of dissolved oxygen profiles collected on each basin of Forest Lake from 2019-2021 provided evidence to suggest that the West Basin did not go anoxic. In comparison, the Middle Basin and East Basin typically stratify at a depth of 15-20 feet from mid-June through early September (Figure 4).

White and light blue areas represent the duration and depths where very little or no oxygen is present. During these times, sediment phosphorus can be released and contribute to internal loading. Subsequently, sediment core locations were identified to gain a representative distribution of samples throughout the portions of each lake basin that are deeper than 15 feet deep.

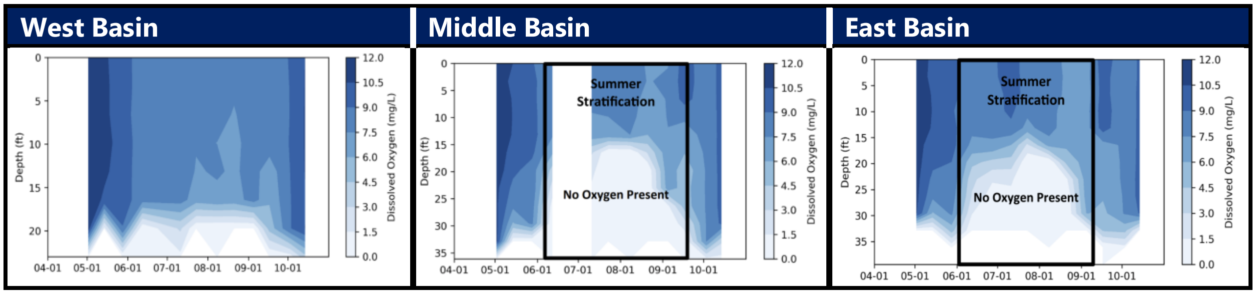


Figure 4. Oxygen profiles at the three basins in Forest Lake.

3.2.4. Sediment Core Releasable Phosphorous (RP) Concentration

Redox-Sensitive Phosphorus is the sum of Labile Phosphorus and Iron-bound Phosphorus fractions. Redox-Sensitive Phosphorus is controlled by stoichiometric redox chemistry and internal loading from this source generally occurs when the sediments and sediment porewater are anoxic. Biogenic Phosphorus (BP) represents the portion of Organic Phosphorous that is currently bound in organic matter, but which is most readily available for dissolution into the water column and is often controlled by biological activity in the sediments.

For each basin, these two sediment sources of phosphorous (Redox-Sensitive and Biogenic) were added to determine the amount of RP available during internal loading events. A review of the RP concentration data provided evidence to suggest that alum dosing rates should be adjusted to target only the amount of phosphorus present within the top 6 cm of the water column.

Sediment RP concentrations were significantly higher in the sediment cores collected from the Middle Basin and the East Basin in comparison with the West Basin. This information, when compiled with bathymetry data, dissolved oxygen data, and bottom hardness data provided additional evidence to suggest that internal loading was not a significant contributor to the overall phosphorus load in the West Basin. Furthermore, the concentration of RP generally decreased with core depth until reaching background concentrations at sediment depths below 6 cm (Figure 5). The RP fractions shown in Figure 5 are the sum of Redox-Sensitive Phosphorous and BP. Table 3 shows numerical values. Observed RP concentrations in the Middle and East Basin were consistently high relative to most Wisconsin and Minnesota Lakes (Table 4). Big Chetac Lake (WI) highlighted in yellow, was the lake that shows similar RP concentration to the Middle and East Basins and was used as a reference to determine the Alum to Phosphorus (AL:P) ratio selected to calculate dosing in this report.

Table 4 shows the ranges in sediment physical-textural characteristics, Redox-Sensitive Phosphorus and Iron-bound Phosphorus concentrations, and the AL:P binding ration ranges in surface sediment. (James and Bischoff, 2015). RP concentrations in Forest Lake were most similar to concentrations observed in Big Chetac Lake, Wisconsin. A 2013 study of Big Chetak Lake (highlighted in yellow in Table 4) found that redox concentrations remained high to a depth of 12 cm in Big Chetac Lake. Therefore, the aluminum sulfate dosage required to inactivate this Redox-Sensitive Phosphorus fraction was 135 g/m. By comparison, the RP concentration of sediment samples from Forest Lake decreased with core depth until reaching background concentrations at sediment depths below 6 cm. This provided evidence to suggest that a lower dosage would be required on Forest Lake (See Section 3.5 [Alum Dosing Recommendations] for final dosage calculations).

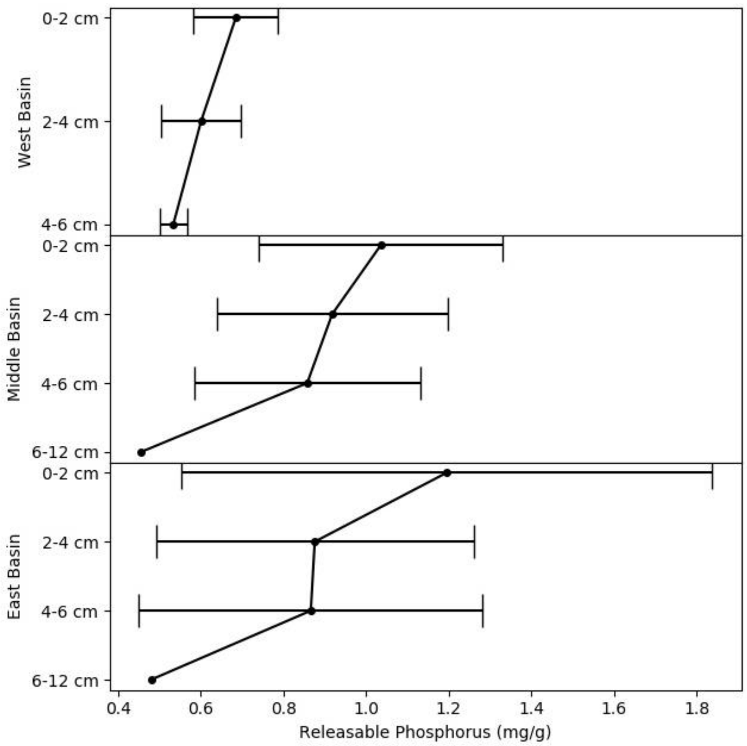
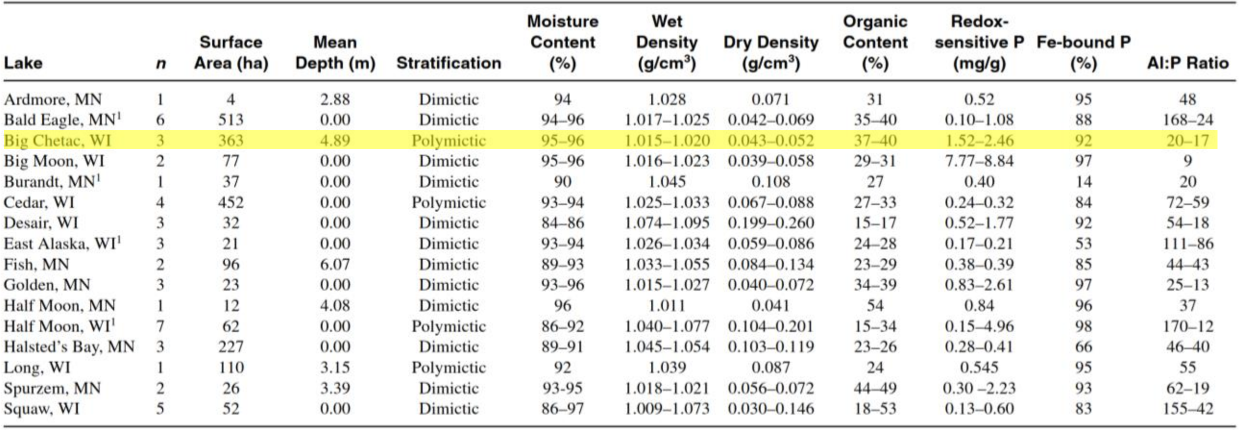


Figure 5. Releasable phosphorus (RP) concentration by sediment core depth showing highest RP concentrations in the first 6 cm of cores.

Table 3. Forest Lake Sediment Core Characteristics

Station	Section		Moisture Content	Wet Bulk Density	Dry Bulk Density	Organic Matter	Redox-P	Bio-labile P	Average RP + Bio-labile P (mg/g)
	(cm)	(cm)	(%)	(g/cm^3)	(g/cm^3)	(%)	(mg/g)	(mg/g)	
East 1	0	2	86.1	1.064	0.151	29.7	2.177	2.473	**0.99**
East 1	2	4	86.1	1.067	0.151	26.9	1.478	1.644	
East 1	4	5	86.8	1.064	0.142	26.1	1.162	1.283	
East 2	0	2	79.7	1.096	0.230	30.2	0.503	0.686	
East 2	2	4	79.1	1.099	0.237	29.7	0.324	0.514	
East 2	4	6	79.0	1.100	0.239	29.6	0.300	0.450	
East 3	0	2	87.4	1.057	0.136	30.6	0.246	0.427	
East 3	2	4	87.6	1.054	0.133	32.4	0.283	0.470	
Mid 1	0	2	83.9	1.074	0.177	29.9	1.313	1.482	**0.93**
Mid 1	2	4	82.4	1.086	0.196	26.7	0.870	1.012	
Mid 1	4	6	85.3	1.071	0.161	26.6	0.669	0.830	
Mid 1	6	7	86.1	1.067	0.151	26.7	0.695	0.856	
Mid 2	0	2	83.5	1.076	0.182	30.7	0.329	0.471	
Mid 2	2	4	84.2	1.072	0.174	30.7	0.351	0.495	
Mid 2	4	5	81.5	1.085	0.207	31.1	0.270	0.402	
Mid 3	0	2	85.5	1.065	0.158	31.1	1.365	1.604	
Mid 3	2	4	86.1	1.063	0.151	30.4	1.471	1.674	
Mid 3	4	5	87.6	1.056	0.134	30.8	1.427	1.637	
Mid 4	0	2	87.0	1.056	0.140	34.1	0.353	0.587	
Mid 4	2	4	85.3	1.064	0.160	33.6	0.321	0.492	
Mid 4	4	5	87.8	1.053	0.131	33.0	0.368	0.562	
West 1	0	2	85.1	1.062	0.163	36.1	0.316	0.583	**0.60**
West 1	2	4	86.1	1.059	0.151	34.7	0.299	0.504	
West 1	4	5	84.7	1.066	0.168	34.7	0.300	0.500	
West 2	0	2	85.4	1.065	0.159	32.1	0.511	0.787	
West 2	2	4	84.1	1.073	0.175	30.8	0.459	0.698	
West 2	4	6	85.4	1.068	0.160	29.3	0.372	0.567	
Validation Cores									
Mid	0	6	92.8	1.034	0.075	26.2	0.627	0.853	------
Mid	6	12	90.4	1.047	0.102	24.7	0.311	0.455	------
East	0	6	92.7	1.033	0.076	28.3	0.655	0.972	------
East	6	12	89.5	1.052	0.112	23.4	0.314	0.480	------

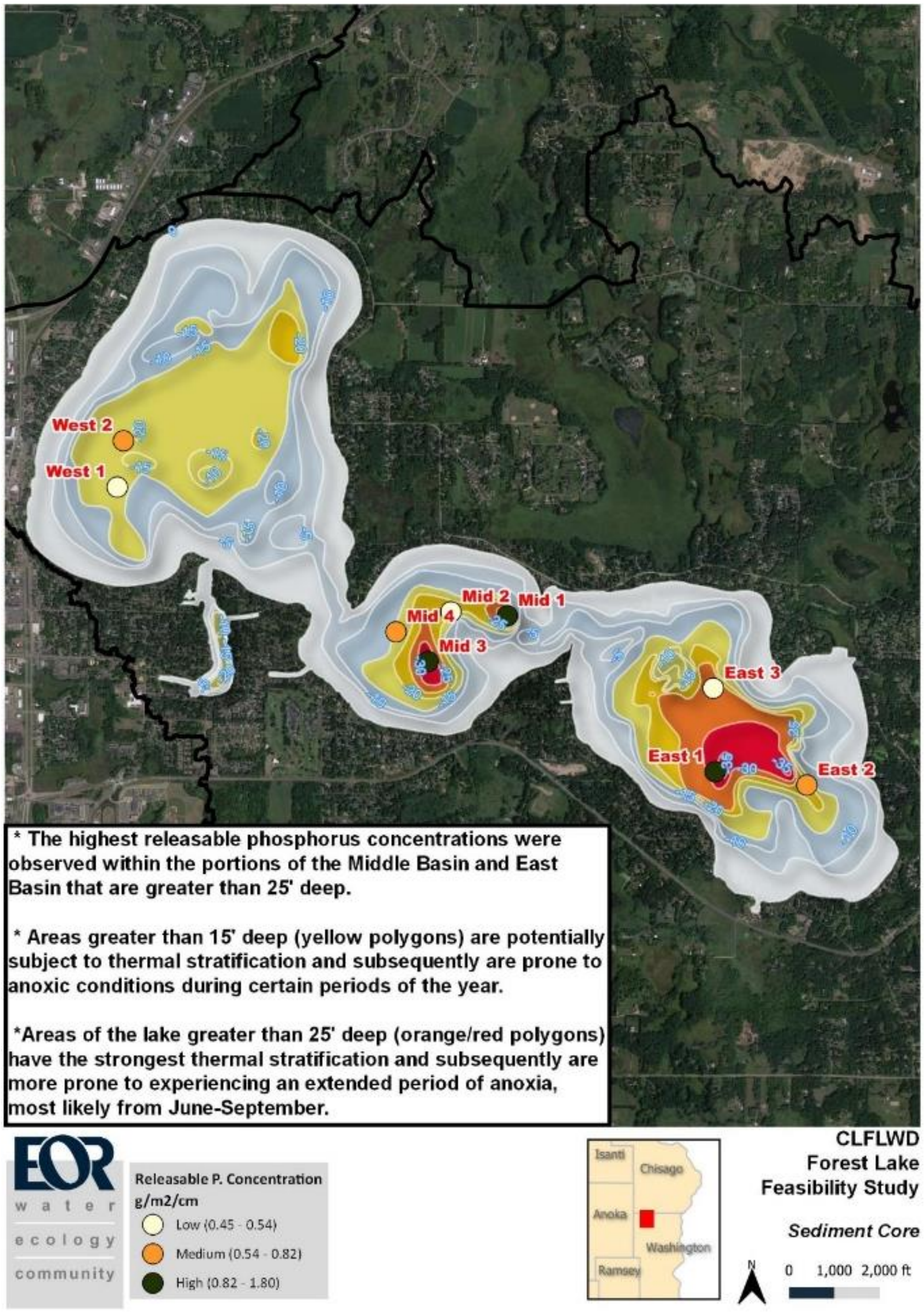
Table 4. Ranges in Sediment Physical-textural Characteristics, Redox-Sensitive Phosphorus (P) and Iron (Fe)-bound Phosphorus Concentrations, and the AL:P Binding Ratio Ranges in Surface Sediment.



Lake	*n*	Surface Area (ha)	Mean Depth (m)	Stratification	Moisture Content (%)	Wet Density (g/cm³)	Dry Density (g/cm³)	Organic Content (%)	Redox-sensitive P (mg/g)	Fe-bound P (%)	Al:P Ratio
Ardmore, MN	1	4	2.88	Dimictic	94	1.028	0.071	31	0.52	95	48
Bald Eagle, MN[1]	6	513	0.00	Dimictic	94–96	1.017–1.025	0.042–0.069	35–40	0.10–1.08	88	168–24
Big Chetac, WI	3	363	4.89	Polymictic	95–96	1.015–1.020	0.043–0.052	37–40	1.52–2.46	92	20–17
Big Moon, WI	2	77	0.00	Dimictic	95–96	1.016–1.023	0.039–0.058	29–31	7.77–8.84	97	9
Burandt, MN[1]	1	37	0.00	Dimictic	90	1.045	0.108	27	0.40	14	20
Cedar, WI	4	452	0.00	Polymictic	93–94	1.025–1.033	0.067–0.088	27–33	0.24–0.32	84	72–59
Desair, WI	3	32	0.00	Dimictic	84–86	1.074–1.095	0.199–0.260	15–17	0.52–1.77	92	54–18
East Alaska, WI[1]	3	21	0.00	Dimictic	93–94	1.026–1.034	0.059–0.086	24–28	0.17–0.21	53	111–86
Fish, MN	2	96	6.07	Dimictic	89–93	1.033–1.055	0.084–0.134	23–29	0.38–0.39	85	44–43
Golden, MN	3	23	0.00	Dimictic	93–96	1.015–1.027	0.040–0.072	34–39	0.83–2.61	97	25–13
Half Moon, MN	1	12	4.08	Dimictic	96	1.011	0.041	54	0.84	96	37
Half Moon, WI[1]	7	62	0.00	Polymictic	86–92	1.040–1.077	0.104–0.201	15–34	0.15–4.96	98	170–12
Halsted's Bay, MN	3	227	0.00	Dimictic	89–91	1.045–1.054	0.103–0.119	23–26	0.28–0.41	66	46–40
Long, WI	1	110	3.15	Polymictic	92	1.039	0.087	24	0.545	95	55
Spurzem, MN	2	26	3.39	Dimictic	93-95	1.018–1.021	0.056–0.072	44–49	0.30 –2.23	93	62–19
Squaw, WI	5	52	0.00	Dimictic	86–97	1.009–1.073	0.030–0.146	18–53	0.13–0.60	83	155–42

3.2.5. Sediment Core RP Concentration with Lake Depth

In addition to differences in RP concentration within the sediment core, there are statistically significant differences (increasing trend) in RP concentrations with depth. The most significant differences in sediment RP content occur at depths greater than 25 feet (Figure 6). This trend of increasing RP concentration with depth justifies ensuring all deep zones within the lake receive alum treatment.



* The highest releasable phosphorus concentrations were observed within the portions of the Middle Basin and East Basin that are greater than 25' deep.

* Areas greater than 15' deep (yellow polygons) are potentially subject to thermal stratification and subsequently are prone to anoxic conditions during certain periods of the year.

*Areas of the lake greater than 25' deep (orange/red polygons) have the strongest thermal stratification and subsequently are more prone to experiencing an extended period of anoxia, most likely from June-September.

Figure 6. Releasable Phosphorus (RP) content within the first 6 cm of the sediment core increases significantly in the portions of the lake that are greater than 25 feet.

3.2.6. Determination of Sediment Phosphorus Release Rates

Upon arrival at the University of Wisconsin-Stout laboratory, three (3) of the 11 sediment cores (one from each basin) were drained of overlying water and the upper 10 cm of sediment was transferred intact and placed in a sediment incubation chamber. Sediment incubation systems consisted of the upper 10 cm of sediment and filtered overlying lake water contained in acrylic core liners that were sealed with rubber stoppers.

The oxidation-reduction environment in the overlying water was controlled by gently bubbling nitrogen through an air stone placed just above the sediment surface in each system in an attempt to simulate an anoxic lake environment. Bubbling action insured complete mixing of the water column but did not disrupt the sediment.

Water samples for soluble reactive phosphorous were collected from the center of each system using an acid-washed syringe and filtered through a 0.45 µm membrane syringe filter. Soluble reactive phosphorous was measured colorimetrically and the rates of phosphorous release from the sediment (mg/m^2 day) were calculated as the linear change in mass in the overlying water divided by time (days) and the area (m^2) of the incubation core liner. Regression analysis was used to estimate rates over the linear portion of the data.

Results

Results from sediment incubation release rate analysis provided further evidence to suggest there are statistically significant differences in sediment phosphorus release rates amongst the three lake basins. The mean rate of phosphorous release under anaerobic (anoxic) conditions was highest in the Middle Basin (Figure 7). The Middle Basin shows anoxic release rates of about 13.14 mg/m^2 day. Aerobic phosphorous release is approximately 12% of anaerobic release for all three basins. Estimated aerobic (oxic) phosphorous release rates are shown in Table 5.

Table 5. Phosphorus Release Rates by Basin

Anoxic phosphorous release (mg/m^2 day)		
East	**Middle**	**West**
8.79	13.14	8.92

Oxic P phosphorous (mg/m^2 day)		
East	**Middle**	**West**
1.05	1.58	1.07

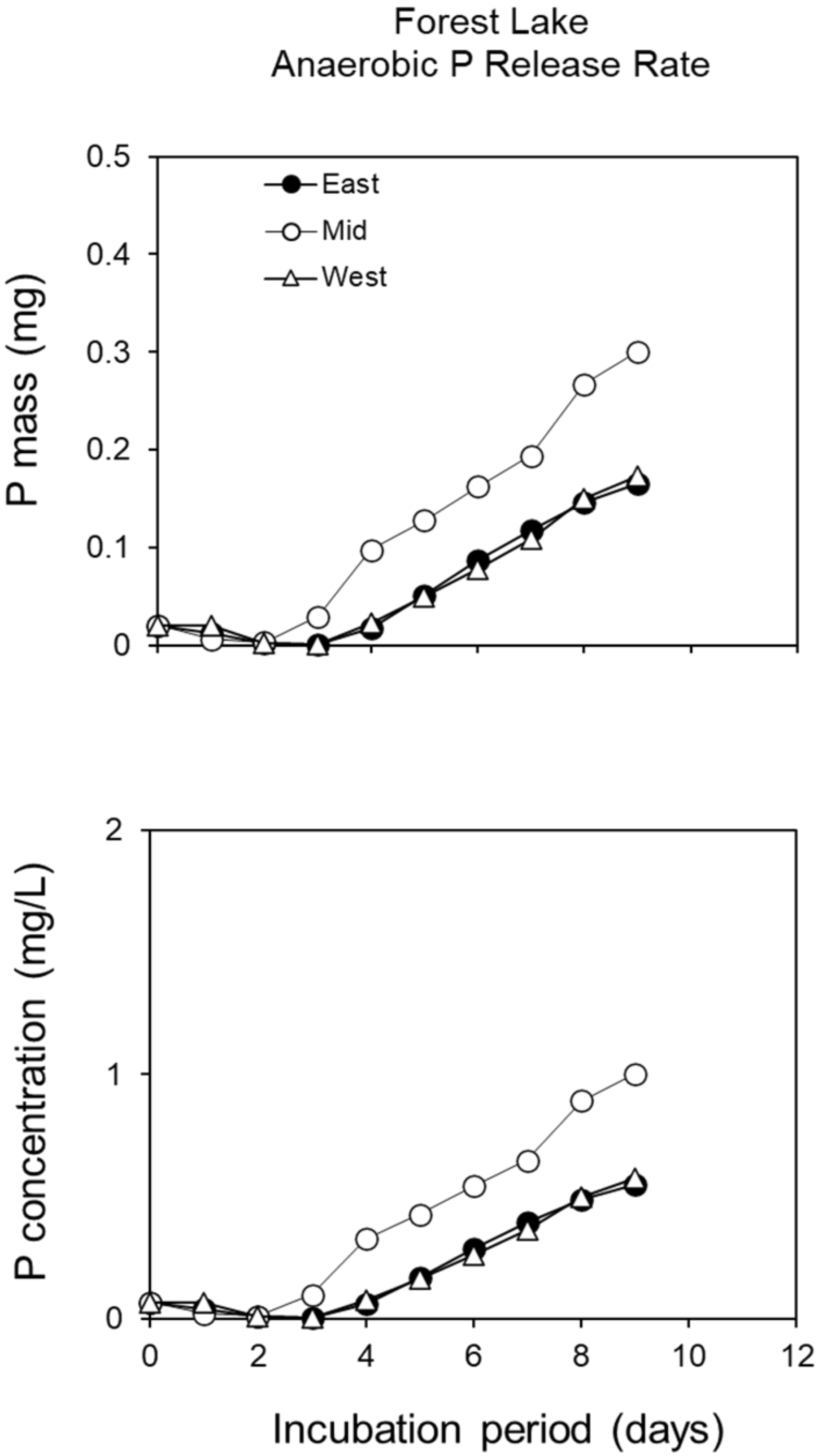


Figure 7. Anaerobic Phosphorus Release Rate by lake basin

Middle Basin

A review of dissolved oxygen data in the Middle Basin provided evidence to suggest that lake sediments are anaerobic for at least 100 days/year in the summer months. Annual anoxic phosphorous loading to the Middle Basin was estimated by multiplying average anoxic release rate measured in the laboratory study (13.14 mg/m^2 day) by the area of the Middle Basin that goes anoxic (428,195 m^2 = ~110 acres) by the assumed days of anoxia (100 days). This yields an estimate of 1,073 lb. for annual anoxic release. The anoxic area (110 acres) roughly corresponds to the area of 15 feet or more depth

A large portion of the phosphorus that is released from the anoxic lake sediments is retained within the hypolimnion and is not mixed with surface waters during the summer growing season. However, some algae, including blue-green algae (cyanobacteria), can migrate vertically in the water column between the epilimnion and hypoliminion because they have flagella (a whip-like tail) or can regulate their buoyancy using gas vacuole structures within the cell. These features offer many competitive advantages including access to internal phosphorus loads by vertical migration into the upper hypolimnion (James, 2016). This vertical migration results in the movement of phosphorus into surface waters. Further, water and nutrient exchanges can occur intermittently during summer stratification due to periodic increases in wind and wave action, or from storm events that result in the cooling of surface waters. The mixing of the water column is strongest during the fall and ultimately leads to complete water column mixing (lake turnover). During turnover, phosphorus that has built up in the hypolimnion is redistributed throughout the water column, occasionally resulting algae blooms in September and October.

Middle Basins sediments were assumed to be aerobic for the remaining 265 days of the year. Annual oxic phosphorus loading was determined by multiplying estimated oxic release rate (1.58 mg/m^2 day) by the area of the Middle Basin that does not go anoxic (1,485,198 m^2= ~261 acres) by the assumed days oxic conditions are present (265 days). This yields an estimate of 1,759 lbs. for annual oxic release. Phosphorus released from oxic sediments is rapidly absorbed by aquatic plants, periphyton, and algae growing along and immediately above the sediment water interface and is not necessarily present in the water column, rather it is constantly cycling through organic matter (plants, algae, fish) living in the lake. Mitigation of oxic sediment phosphorus release is best achieved by establishing and maintaining a healthy aquatic plant community that can retain phosphorus, thereby competing with algae and maintaining a clear-water state.

East Basin

A review of dissolved oxygen data in the East Basin provided evidence to suggest that lake sediments are anaerobic for at least 100 days/year in the summer months. Annual anoxic phosphorous loading to the East Basin was estimated by multiplying average anoxic release rate measured in the laboratory study (8.79 mg/m^2 day) by the area of the lake that goes anoxic (737,877 m^2= ~182 acres) by the assumed days of anoxia (100 days). This yields an estimate of 1,237 lbs. for annual anoxic release. The anoxic area (182 acres) roughly corresponds to the area of 20 feet or more depth.

East Basin sediments were assumed to be aerobic for the remaining 275 days of the year. Annual oxic phosphorous loading was determined by multiplying estimated oxic release rate (1.05 mg/m^2 day) by the area of the basin (3,152,504 m^2 = ~597 acres) by the assumed days of anoxia (275 days). This yields an estimate of 2,516 lbs. for annual oxic release.

3.3. Forest Lake Water Quality

Since 1984, in-lake water quality conditions have been monitored in Forest Lake. In-lake water quality conditions include the primary nutrient contributing to algae blooms in freshwater lakes, total phosphorus (TP); two response variables indicating the magnitude of algae growth in lakes, chlorophyll-a, and Secchi disk depth; and basic water chemistry characteristics measured throughout the water column including dissolved oxygen, conductivity, and pH.

In the State of Minnesota, the growing season average, June through September, for the most recent ten-year period is used to assess the current water quality conditions in lakes. A lake does not meet State standards if TP and either chlorophyll-a or Secchi disk depth do not meet designated concentrations. The most recent ten-year growing season average concentrations (2012-2021) for the three Forest Lake basins are shown in Table 6. The West Basin has the best water quality of all three lakes meeting state standards for all three parameters. The Middle Basin and the East Basin also meet TP standards however, TP concentrations are closer to the state standard of 40 µg/L and chlorophyll-a exceeds the state standard of 14 µg/L (Table 6). Furthermore, TP and chlorophyll-a concentrations in the Middle Basin and the East Basin may be worsening in the past ten-years, however, neither trend is statistically significant at this point (Table 7).

Table 6. Forest Lake Ten-year Growing Season (June-Sept.) Average for Total Phosphorus, Chlorophyll-a, and Secchi Disk Depth (2012-2021)

	Total Phosphorus (µg/L)	Chlorophyll-a (µg/L)	Secchi Disk Depth (ft)
State Standard	<40	<14	>4.6
Forest – West	30.8	12.7	4.8
Forest - Middle	35.9	14.9	6.3
Forest - East	34.5	18.4	6.5

Table 7. Forest Lake Water Quality Trends

Lake	Total Phosphorus Trend	Chlorophyll-a Trend	Secchi Disk Trend
Forest – West	Improving since 1984 **Significantly Improving since 2012**	**Significantly Improving since 2001**	Improving since 1984 **Significantly Improving since 2012**
Forest – Middle	*Worsening since 2012*	*Worsening since 2012*	Improving since 2012
Forest – East	*Worsening since 2012*	*Worsening since 2012*	**Significantly Improving since 2012**

Short-term trends are noted for the most-recent 10-years (since 2012)

Long-term trends are noted for the period of record for each lake, which varies, with the earliest year noted

With the surface water quality in the Middle Basin and East Basin near the state standards and short-term trends potentially suggesting water quality may be beginning to worsen, although not statistically significantly, additional bottom phosphorus concentrations were collected during the 2018 through 2021 monitoring seasons. As mentioned before, bottom phosphorus concentrations are collected to identify if phosphorus stored in the sediment of the lakes is contributing to poor surface water quality. Bottom phosphorus stored in lake sediments is released during the growing season and sometimes over winter when the lake stratifies, and the bottom water goes anoxic.

For bottom water phosphorus concentrations only orthophosphate concentrations are measured because orthophosphate is a dissolved portion of TP. Dissolved chemicals have the potential to move throughout the water column impacting surface water quality. Large concentration gradients between the bottom water and surface water created when bottom phosphorus concentrations exceed 100 µg/L can accelerate this movement. The observed depth of anoxic water, bottom orthophosphate, and surface TP for all three basins are shown in Figure 8, Figure 9, and Figure 10. In each figure, the top graph shows the estimate depth where the dissolved oxygen concentration is approximately 1 mg/L which was used to identify water close to anoxic conditions when phosphorus may be released from bottom sediments, the middle graph shows the bottom orthophosphate concentrations, and the bottom graph shows the surface TP concentrations. Increases in both bottom orthophosphate and surface TP is an indication that phosphorus release from the bottom sediments may be impacting surface water quality.

In the West Basin, oxygen remains present at the bottom of the lake for most of the year. Anoxic conditions only occur, if at all, in mid to late July. These brief anoxic conditions result in a minor increase in bottom orthophosphate, with no observable increase in surface TP (Figure 8).

In the Middle Basin, the lake becomes stratified starting around the third week of May and lasts until Autumn turnover around the beginning of September. Anoxic conditions start forming in the deepest portion of the lake that are greater than 25 feet in May. By the third week of June, a thermocline develops at a depth of 15 feet. Anoxic conditions persist below 15 feet until fall turnover or a mixing event that can occur from excessive wind. A mid-season mixing event may have occurred in 2019. Two of the four years, 2020 and 2021, showed evidence that bottom orthophosphate may be contributing to increasing surface TP concentrations in the Middle Basin with increases in both concentrations (Figure 9).

Anoxic conditions in the East Basin follow a similar pattern as the Middle Basin, beginning around the third week of May, progressing until the third week in June, and remaining stable until the beginning of September. However, the stable anoxic depth in the East Basin is more variable and deeper than Middle Basin with a thermocline depth closer to 20 feet below the water surface. The increased variability and deeper anoxic depth are likely a result of East Basin having a larger surface area which increases the influence of wind driven wave action and mixing in comparison with the smaller Middle Basin. Only one year, 2021, in the East Basin had increasing bottom orthophosphate concentrations that correlated with similarly increasing surface TP concentrations (Figure 10).

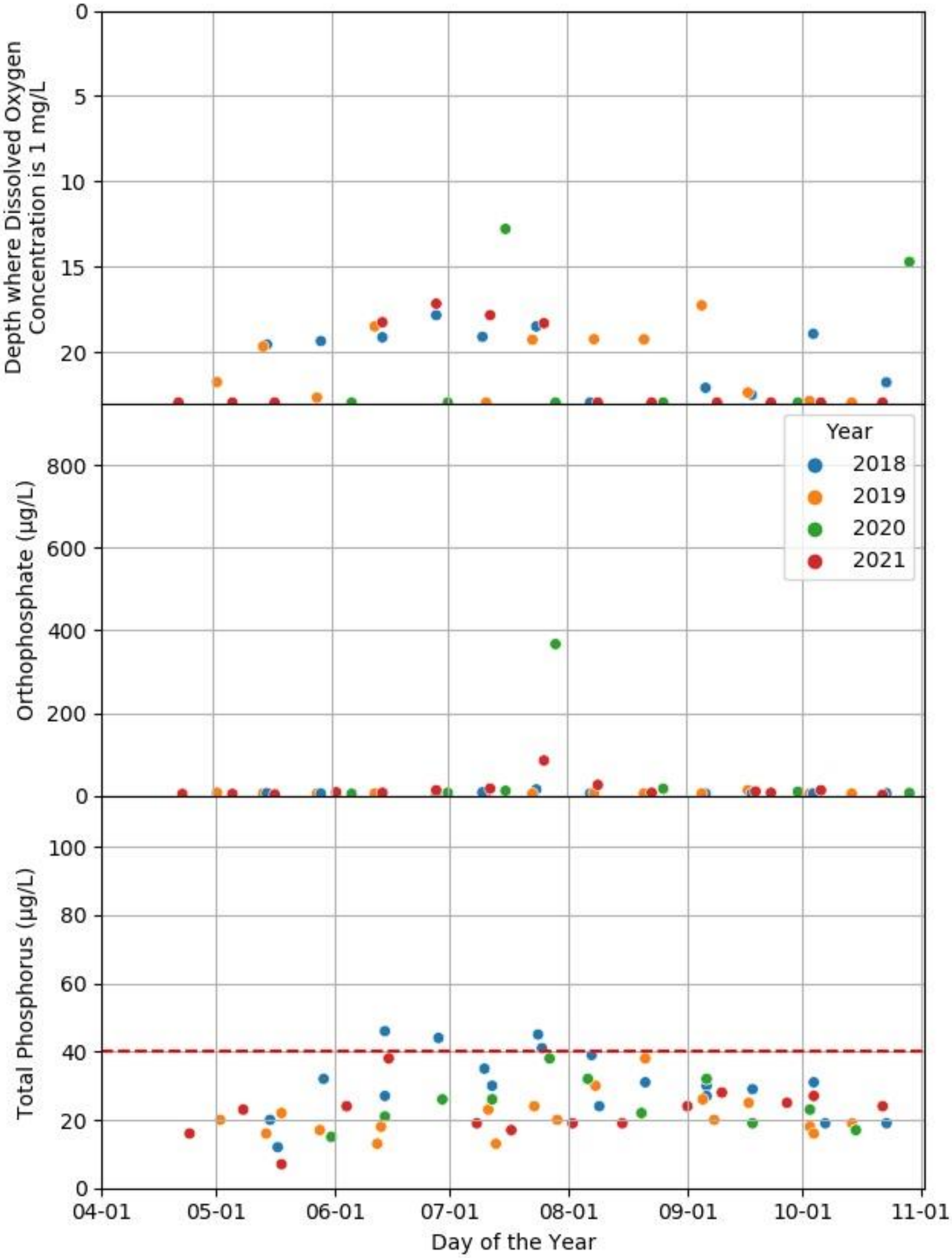


Figure 8. Forest-West anoxic water depth, bottom orthophosphate and surface TP concentrations, 2018-2021.

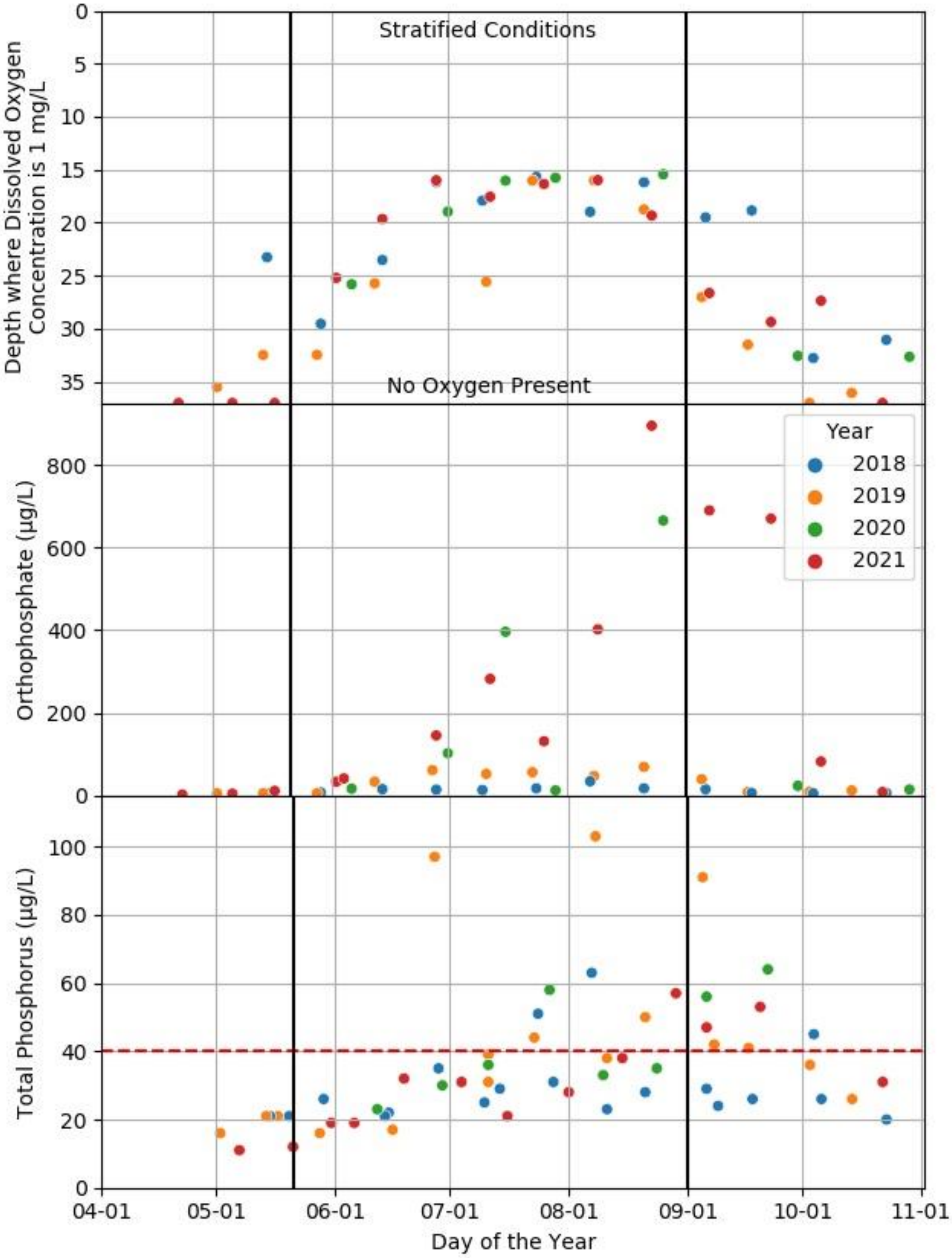


Figure 9. Forest-Middle anoxic water depth, bottom orthophosphate and surface TP concentrations, 2018-2021.

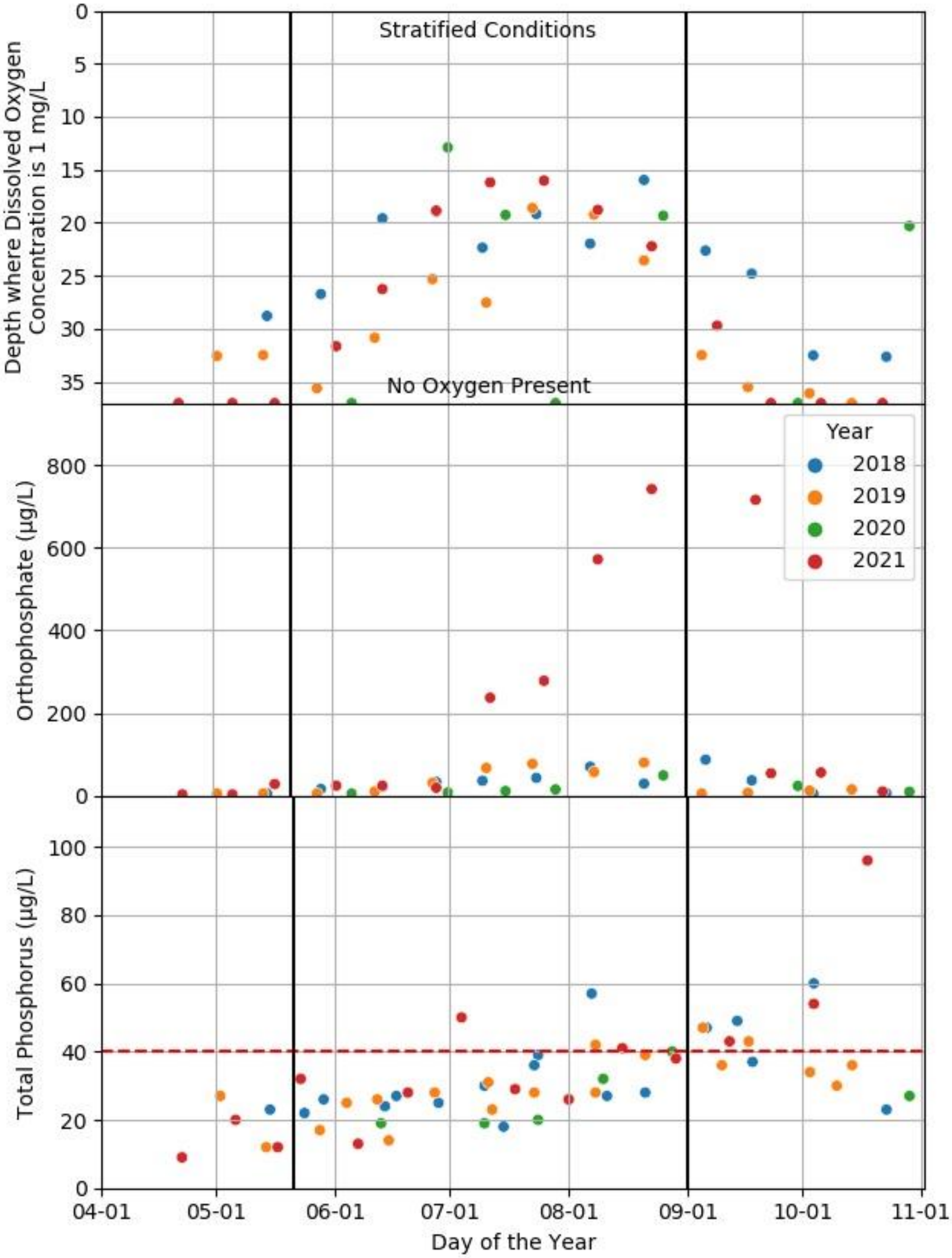


Figure 10. Forest-East anoxic water depth, bottom orthophosphate and surface TP concentrations, 2018-2021.

3.4. Lake Response Modeling Update

The Forest Lake response model was updated using modeling software BATHTUB (Version 6.1) which links phosphorus loads with in-lake water quality. BATHTUB is a steady-state annual or seasonal model that predicts a lake's summer (June through September) mean surface water quality. BATHTUB's time-scales are appropriate for this study because watershed phosphorus loads are determined on an annual or seasonal basis, and the summer season is critical for lake use and ecological health. The heart of BATHTUB is a mass-balance phosphorus model that accounts for water and phosphorus inputs from tributaries, watershed runoff, the atmosphere, sources internal to the lake, and groundwater; and outputs through the lake outlet, water loss via evaporation, and phosphorus sedimentation and retention in the lake sediments.

In typical applications of BATHTUB, lake and reservoir systems are represented by a set of segments and tributaries. Segments are the basins (lakes, reservoirs, etc.) or portions of basins for which water quality parameters are being estimated, and tributaries are the defined inputs of flow and pollutant loading to a particular segment. For this study, each Forest Lake Basin (West, Middle, and East) was represented as a separate segment, and each phosphorus source was represented as individual tributaries to each basin. The Canfield-Bachmann phosphorus sedimentation model (Canfield and Bachmann 1981) best represents the lake water quality response of Minnesota lakes and was used for this study.

The input required to run the BATHTUB model includes lake geometry, climate data, and water quality and flow data for phosphorus sources to the lake. Climate data was updated using annual precipitation estimates from the PRISM Climate Group and evaporation estimates from the University of Minnesota St. Paul. Change in storage for the scenarios were updated using lake water level elevations reported in the DNR Lake Finder. Groundwater data was estimated from flow monitoring completed in 2016 and 2021. The division of groundwater amongst the basins and the TP concentrations in the groundwater followed the assumptions used in the 2007 CLFLWD Capital Improvement Plan Lake Response Model (http://www.clflwd.org/documents/CLFLWDWQStudy-CIPPlan_Wenck_2007.pdf). Watershed P loads were based on monitoring data from 2016 and 2021. The two monitoring years happen to represent a wet year, 2016, with 39.4 inches of precipitation and a dry year, 2021, with 17.9 inches of precipitation.

The Forest Lake BATHTUB model was calibrated to an average precipitation year for the period 2012-2021. Total inflow to Forest Lake was approximated by completing a 10-year water balance between 2012 and 2021 using average annual precipitation, evaporation, average flow volume measured at the Forest Lake outlet and change in water level over the ten-year period. The total inflow to Forest Lake was estimated to be 6,430 ac-ft/yr which was divided amongst groundwater and tributary flow using the average percentage of flow that each source contributed for 2016 and 2021.

Tributary TP concentrations were estimated as the flow weighted average between 2016 and 2021. The updated climate inputs to the BATHTUB model are shown in Table 8. The estimated relative volume and TP load allocation for each basin are shown in Figure 11.

The advective inflow and net diffusive inflow in Figure 11 represent the exchange of TP and volume between the three basins. The largest sources of volume and TP load vary by basin. The East basin, the most upstream basin, receives the largest portion of TP from tributary sources with the largest portion coming from the WJD-6 tributary. The largest sources of TP to the Middle Basin are a mixture of in-lake phosphorus exchange (i.e., internal load) and load from the East Basin, and tributary sources, namely the Shields Lake drainage. The West Basin receives the majority of TP from the other two basins Figure 11.

Table 8. BATHTUB Climate Inputs.

Parameter	Average Year (2012-2021)
Precipitation (in/yr)	39.4
Evaporation (in/yr)	34.5
Change in Storage (in/yr)	-0.7
Atmospheric Deposition (kg/ha/yr)	0.12 kg/ha/yr

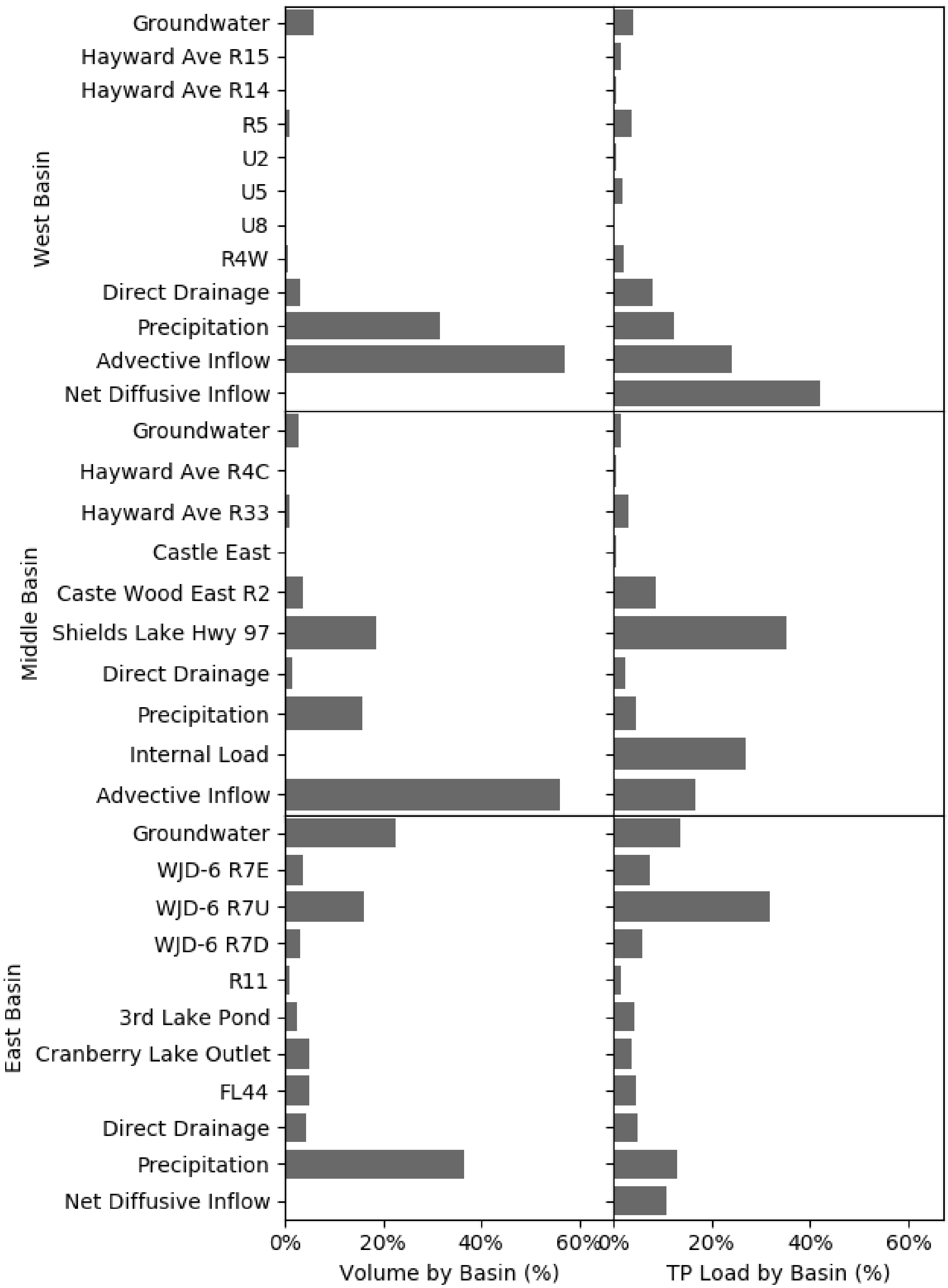


Figure 11. Average year relative water and total phosphorus balances for each Forest Lake basin (%).

The uncalibrated model overestimated in-lake TP concentrations in all three basins. The calibration of the model was informed by the sediment core data and the hypolimnion and epilimnion monitoring data which showed that the West Basin had little to no internal loading and the Middle Basin had the most evidence of internal loading. From that information, the sedimentation rate in the West Basin was increased and excess internal loading was added to the Middle Basin to balance the changes in predicted in-lake TP concentrations. Excess internal loading was not needed in the East Basin for calibration and the sedimentation rate in the basin was increased. The internal load that needed to be added in the Middle Basin to achieve calibration, supports the need for alum treatment in the basin.

A summary of the calibration and the observed and predicted in-lake TP concentrations are shown in Table 9 The calibrated phosphorus balance for the model is shown in Table 10.

Table 9. Basin Calibration for In-lake TP Concentrations

Basin	Average Year (2012-2021)		
	Calibration	**Observed In-lake TP (µg/L)**	**Calibrated In-lake TP (µg/L)**
West	Increase P sedimentation by 1.79x	30.8	30.8
Middle	0.44 mg/m2-day excess internal load	35.9	35.9
East	Increase P sedimentation by 1.225x	34.5	34.5
	Area Weighted Average	32.9	33

Table 10. Average year (2012-2021) Updated Existing Total Phosphorus Loads by Basin

Phosphorus Source	Forest Lake West		Forest Lake Middle		Forest Lake East	
	lb/yr	**% total**	**lb/yr**	**% total**	**lb/yr**	**% total**
Atmospheric Deposition	258.6	*12%*	88.4	*5%*	187.6	*13%*
Watershed Runoff	384.0	*18%*	982.2	*50%*	924.2	*63%*
Calibrated Excess Internal Load*	0	*0%*	526.7	*27%*	0	*0%*
Groundwater	80.5	*4%*	27.6	*1%*	196.7	*13%*
Upstream Lakes	507.1	*24%*	328.0	*17%*	0	*0%*
Net Diffusive Inflow**	887.8	*42%*	0	*0%*	155.6	*11%*
Total	**2118.0**		**1952.9**		**1464.1**	

** The calibrated excess internal load represents the internal load that is above what is expected for a normal lake at a certain trophic state. All lakes have a natural, background level of internal loading (sediment phosphorus release), this background internal load is implicitly included in the BATHTUB model. Therefore, internal loading rates added to the BATHTUB model during calibration represents the excess sediment release rate beyond the average background release rate accounted for by the model development lake dataset.*

*** This represents the net flow of phosphorus between the Forest Lake Basins through phosphorous concentration gradients between the basins in addition to through the movement of water. The Middle Basin contains the highest phosphorus concentrations, therefore, there's no diffuse inflow for the Middle Basin.*

The load reduction from alum dosing to the Middle Basin of Forest Lake was estimated by removing the excess internal load from the calibrated BATHTUB models. The predicted load reductions and in-lake TP concentrations are shown in Table 11. The predicted load inactivated from an alum treatment to the Middle Basin was estimated to be approximately 527 lb./yr for the average year. The alum dosing will benefit all three basins in the lake with in-lake TP concentrations decreasing in each basin. With the full alum treatment in the Middle Basin, the predicted area average in-lake TP concentration for Forest Lake is expected to be very close to meet the District's goal of 30 µg/L. However, close monitoring of the actual effectiveness of the proposed split dosing in the Middle Basin needs to occur to inform any needed adaptive management.

Table 11. Predicted in-lake Total Phosphorus concentrations.

	Forest Lake West	Forest Lake Middle	Forest Lake East
Average Year in-lake TP (µg/L)	**30.8**	**35.9**	**34.5**
Predicted in-lake TP (µg/L)	28	31.7	31.9
Load Reduction (lb/yr)	527		

3.5. Alum Dosing Recommendations

The weight of evidence approach provided the background information needed to identify a treatment zone which consisted of the portions of the Middle Basin that are deeper than 15 feet.

3.5.1. Middle Basin

Treatment of the Middle Basin requires targeting the top 6 cm of the sediment column within the portion of the Middle Basin that is deeper than 15 feet (110 acres) using an alum to phosphorus (AL:P) binding ratio of 20:1. The AL:P binding ratio was calculated using the maximum observed Redox-P + Biolabile-P concentration of 1.674 mg/g within the Middle Basin (Figure 12 left). Observed Redox-P + Biolabile P concentrations for all sediment cores are shown in Table 3 of this report.

The treatment requires the application of 74,000 gallons of alum at an average alum dosing rate of 670 gallons per acre and 36,700 gallons of sodium aluminate buffer at an average dosing rate of 340 gallons per acre. These are the application rates needed to bind at least 90% of the redox-sensitive P. The required Al dosage is 90 g Al/m^2 (Figure 12 right). The gray shaded area denotes the range in Al dosage over the 4–10 cm sediment layer thickness for the mean redox-P concentration ± the 95% confidence interval. Source: James and Bischoff, 2015. The dosage was determined based on the alum to phosphorus binding ratios by James and Bischoff (2015) using concentrations of redox- sensitive phosphorus to calculate this ratio.

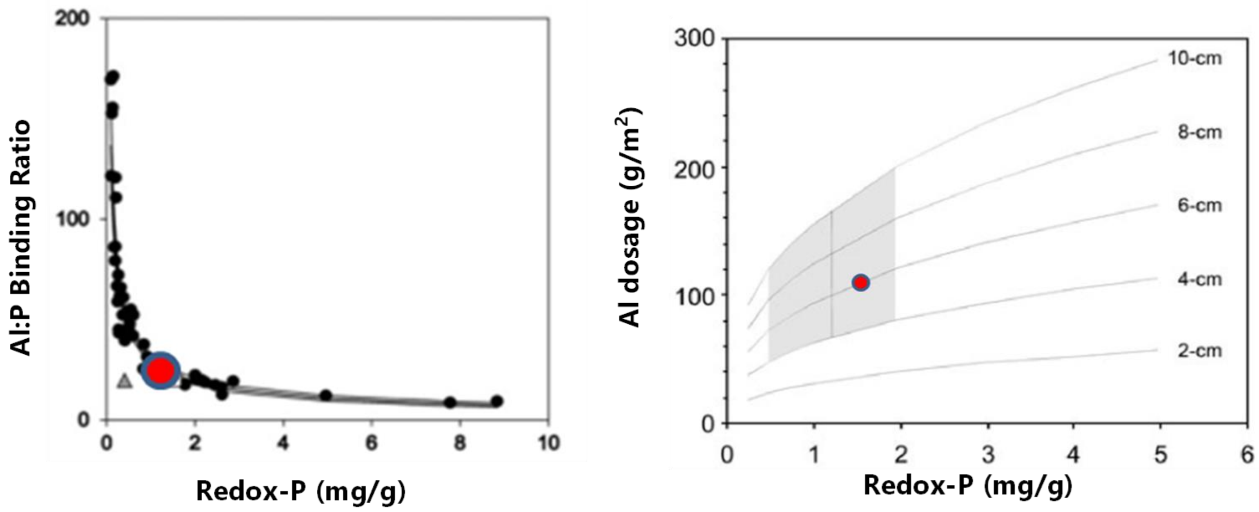


Figure 12. Left: Relationship between the redox-sensitive phosphorus concentration and the aluminum (Al) to Phosphorus (P) ratio. **Right:** Relationships between the mean redox-sensitive phosphorus (redox-P) and Al dosage. Red dots represent the maximum (1.674 mg/g) redox-P + biolabile P concentration observed in sediment cores collected from the Middle Basin in 2022.

3.5.2. Middle Basin & East Basin

As mentioned in Section 3.4 [Lake Response Modeling Update], BATHTUB modeling of the average precipitation year indicated that Al treatment in the Middle Basin would also reduce the in-lake P concentration in the East and West Basins (Table 11) by about 3 µg/L. This is due to the connection among the three basins. Therefore, the need for a potentially expensive Al treatment in the East Basin (see Section 3.5.3 [Costs]) is reduced.

Treatment of the RP content within the top 6 cm of the sediment column within the portion of the Middle Basin and East Basin that is deeper than 15 feet (374 acres) using an alum to phosphorus binding ratio of 20:1 requires the application of 280,000 gallons of alum at an average alum dosing rate of 750 gallons per acre and 140,000 gallons of sodium aluminate buffer at an average dosing rate of 380 gallons per acre.

3.5.3. Costs

A range of costs for the alum dosing application are shown in Table 12. Costs are based on a minimum cost of $1.93 per gallon of alum and include labor and equipment. For planning purposes, the costs have been increased by 15%. Costs do not include administration, permitting, or other management activities.

EOR recommends treating only the Middle Basin at this time and split the total dosage into two applications to test the assumed contributions from Labile Organic Phosphorus. If that contribution is lower than assumed in this report, the second application may not be needed, the application area could be reduced, or the required alum concentration could be lowered. It is important to note that the costs presented for the split dosing method assume that only 50% of the total alum dose is applied during the initial application. The second application would be applied two years after the initial application. Increases in the price of materials and labor over this two-year period would increase the costs of the second application and overall expenditure.

Additional monitoring following the first dose is recommended to determine the effectiveness of the first treatment and if dosing adjustments are required for the second treatment. Labile Organic Phosphorus consists of organic matter that is not strongly attached to sediment that will be broken down over time and eventually become bioavailable to algae. Controlling Labile Organic Phosphorus represents a commitment to extending the life expectancy of the alum treatment.

Table 12. Alum Dosing Estimate.

Middle Basin Full Dosing Method	2022 Cost	2022 Cost + 15%
Water column stripping and 2 cm x 110 acres treated sediment	$215,883	$248,265
Water column stripping and 4 cm x 110 acres treated sediment	$336,310	$386,757
Water column stripping and 6 cm x 110 acres treated sediment	$483,921	$556,509
Middle & East Basin Full Dosing Method	**2022 Cost**	**2022 Cost + 15%**
Water column stripping and 2 cm x 374 acres treated sediment	$751,036	$863,691
Water column stripping and 4 cm x 374 acres treated sediment	$1,301,433	$1,496,648
Water column stripping and 6 cm x 374 acres treated sediment	$1,845,861	$2,122,740
Middle Basin Split Dosing Method	**2022 Cost**	**2022 Cost + 15%**
Water column stripping and 2 cm x 110 acres treated sediment	$107,942	$124,133
Water column stripping and 4 cm x 110 acres treated sediment	$168,155	$193,378
Water column stripping and 6 cm x 110 acres treated sediment	$241,960	$278,254
Middle & East Basin Split Dosing Method	**2022 Cost**	**2022 Cost + 15%**
Water column stripping and 2 cm x 374 acres treated sediment	$375,518	$431,846
Water column stripping and 4 cm x 374 acres treated sediment	$650,716	$748,323
Water column stripping and 6 cm x 374 acres treated sediment	$922,930	$1,061,370

The orange highlighted cell displays costs for the recommended approach. The highlighted cell only represents the costs associated with the first treatment. Future costs are subject to fluctuations in costs of materials and labor.

3.5.4. Longevity Analysis

Brian Huser of the Swedish University of Agricultural Sciences, Department of Aquatic Sciences conducted an analysis of 114 lakes treated with alum to identify factors driving the longevity of post-treatment water quality improvements. The following three variables: 1) Al dosage rate, 2) watershed to lake area ratio, and 3) lake morphology explained 82% of the variation in treatment longevity based on post-treatment changes in TP concentration (Huser et., al, 2011).

Treatment longevity based on declines in epilimnetic total P (TP) concentration averaged 11 years for all lakes (range of 0-45 years). Significant differences in treatment longevity between deeper, stratified lakes (mean 21 years) and shallow, polymictic lakes (mean 5.7 years) were detected. A review of dissolved oxygen profiles provided strong evidence to suggest that the Middle Basin is a stratified waterbody. The watershed of Forest Lake is 8,160 acres. The surface area of Forest Lake is 2,289 acres. Dividing the watershed area by the lake's surface area yields a Watershed to Lake Area (WA:LA) ratio of 3.56. Huser found that lakes like Forest Lake, with WA:LA ratios less than 8.8, average longevity increased to 26 years. Finally, Huser found that an alum dosage rate above 15 g/m^{-2} was a critical variable in predicting the longevity of the alum treatment. The recommended dosage rate of 90 g/m^{-2} for the Middle Basin is exactly 6 times larger than the 15 g/m^{-2} threshold. Based on these factors, the proposed treatment of the Middle Basin should reduce epilimnetic TP for a minimum of 10 years and potentially longer. Further, EOR is recommending the total alum dosage be split into two separate applications to control Labile Organic Phosphorus to extend the life expectancy of the alum treatment

4. OTHER PHOSPHORUS MANAGEMENT ALTERNATIVES

4.1. Hypolimnetic Aeration

The hypolimniom is the deeper portion of a lake where the water is stagnant and essentially uniform temperature. In this zone the water down near the sediment can become oxygen deprived as accumulated organic matter is broken down by microorganisms. In these modified conditions, the natural ability of sediments to bind with phosphorus is altered and the phosphorus is released to the water column becoming available in the lake to algae. Hypolimnetic aeration is a phosphorus cycling control technique whereby P rich anoxic sediments in the hypolimnion are oxygenated with a mechanical aeration system preventing an anaerobic condition that leads to release of P.

Hypolimnetic aeration has been proven successful in reducing contributions of phosphorus from lake sediments with sufficiently high iron to phosphorus concentrations such as Vadnais Lake which serves as a municipal drinking water source for the City of St. Paul. In many lakes, additions of iron are required to supplement hypolimnetic aeration to sufficiently bind phosphorus present within the sediment pool.

In Forest Lake, a portion of the internal loading from lake sediments is due to the shallow nature of the lake from physical mixing due to wind, wave action, and recreation. Further, sediments release phosphorus, even under oxygenated conditions. A more sustainable approach relies on the conversion of Forest Lake to a clear-water, aquatic plant dominated state following the addition of alum and re-establishment of native vegetation throughout the littoral zone. Hypolimnetic aerators would need to be run in perpetuity to control releases of labile phosphorus within the hypolimnion which would also likely require the addition of iron to maintain high levels of iron in the lake sediment.

Unlike aeration, the alum plan presented permanently binds a mass of RP. While hypolimnetic aeration may have similar or less upfront costs in comparison to alum, the continued annual operation and maintenance cost of $69,000-$87,000 (2022-dollars) are an expense that would be incurred in perpetuity as these systems are only effective so long as the aeration units are running. Over a 10-year period, the operational costs of the aeration system could add another $870,000 or more. Therefore, at this point hypolimnetic aeration is not recommended for Forest Lake.

4.2. Sediment Dredging

Analysis of lake sediment RP concentrations identified high RP levels in multiple locations dispersed throughout the lake. Excavation of nutrient rich sediment represents a practicable opportunity in environments where high concentrations of RP are relegated to confined areas. However, given the distribution of high RP concentration at multiple locations, this options quickly became impractical (high associated cost) for any of the basins of Forest Lake.

5. AQUATIC VEGETATION MANAGEMENT

5.1. Background

Aquatic vegetation is a vital component of lake ecosystems. Healthy aquatic plant communities sustain water quality and support ecological function. Threats to healthy aquatic plant communities include invasive species, water quality degradation, shoreline development, and recreation. These impacts affect the ecosystem services provided by native aquatic vegetation. For example, curly-leaf pondweed (CLP) can contribute to internal loading.

Following an alum treatment, water clarity would be expected to increase at Forest Lake. However, as shown in Table 7, water clarity has already been improving in all three basins of Forest Lake since 2012 with statistically significant trends in the two basins with the largest littoral zones (East Basin and West Basin). As a result, aquatic plants already grow to a depth of 15 feet in both basins.

The proposed alum treatment may allow aquatic vegetation to grow at depths exceeding 15 feet and may result in an overall increase of aquatic vegetation biomass within the portions of the lake that are less than 15 feet deep.

The anticipated increase in aquatic vegetation growth could result in an increased costs of aquatic plant management, lake-user navigational and aesthetic concerns, and the loss of the ecological functions provided by native aquatic communities. It is also possible that increased water clarity provides an open niche for a native aquatic plant community to expand.

In 2023, the CLFLWD will develop and maintain a proactive lake vegetation management plan for Forest Lake. The Forest Lake Vegetation Management Plan (FLVMP) will build upon the annual pre-treatment and post-treatment survey work already being completed by Blue Water Science. Further, the LVMP will explore the positive and negative aspects of various aquatic plant management techniques and establish lake specific aquatic plant management goals that are in line with the District’s AIS Management Plan. Finally, the FLVMP will identify quantifiable goals to maintain accountability and to assess the effectiveness of implemented treatment options.

Proactively addressing aquatic plant management issues as part of a commitment to future in-lake management not only will help plan for baseline aquatic management, but also provide opportunity for long-term resilience to water quality and invasive plant issues. The alum treatment presents a long-term opportunity for securing the water quality of Forest Lake into the future. Creating a robust and resilient native aquatic plant community that mitigates the impacts of colonization by invasive aquatics, especially the negative water quality impacts associated with CLP can help to increase the longevity of the alum treatment by further reducing the lake’s internal nutrient load. .

5.2. Current Aquatic Plant Management at Forest Lake

Two submerged invasive aquatic plant species, CLP and EWM are managed at Forest Lake (in addition to the emergent invasive plant, flowering rush). Management has focused on herbicide treatment of these two target species.

Curly-leaf Pondweed (CLP)

CLP treatments have ranged from 16 to 169 acres from 2009 through 2021 with variability from year to year (Figure 13). Over 120 acres were treated in 2021 at a cost of $28,335 ($236/acre) including delineation and treatment.

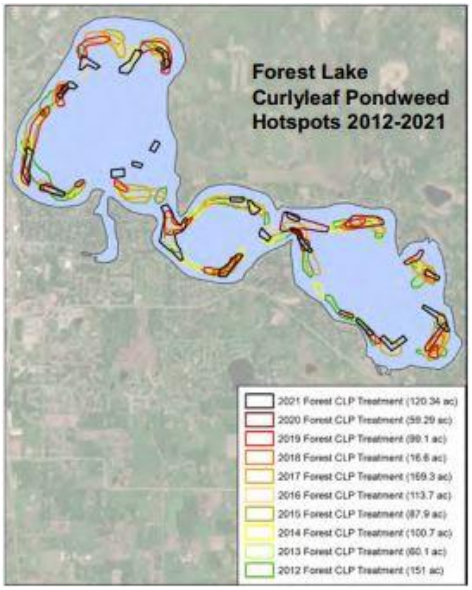


Figure 13. Forest Lake CLP Hotspots (2012-2021) from CLFLWD 2021 Aquatic Invasive Species Report.

Eurasian Watermilfoil (EWM)

EWM was discovered in Forest Lake in 2015 and 30 acres were treated in the first year. From 2016 through 2021, EWM treatments have ranged from 8.37 acres to 53.83 acres (Figure 14). EWM has been confined mostly to the West Basin but there is some growth in the Middle Basin at the end of 2021. The greatest number of acres treated were in 2020 (53.82 acres). A total of 8.37 acres were treated in 2021 using a combination of ProcellaCOR and diquat.

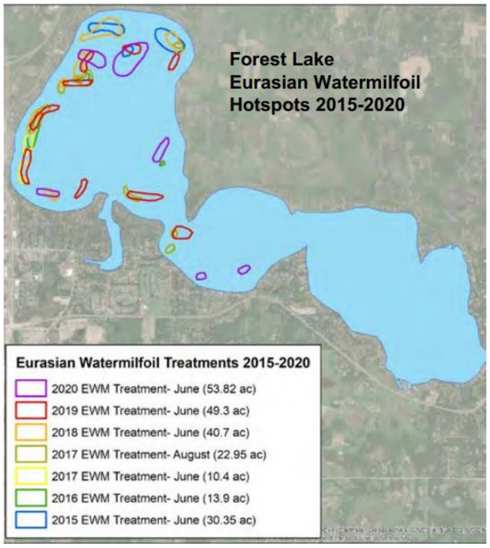


Figure 14. Forest Lake EWM Hotspots (2015-2020) from CLFLWD 2021 Aquatic Invasive Species Report.

5.2.1. Anticipated Changes in Aquatic Vegetation

Increases in water clarity following a reduction in internal loading will likely result in an increase in the abundance and distribution of submerged aquatic plants in Forest Lake. The extent and magnitude of changes will likely be variable based on the effect of the alum treatment on clarity across the three basins as well as other environmental factors like bottom hardness. Broadly speaking, surveys of aquatic vegetation conducted in Minnesota and Wisconsin lakes following alum treatments have seen an initial burst of aquatic plant growth in the years immediately following the alum treatment (Steve McComas, Blue Water Science).

Several example case studies are discussed below. These case studies are provided only as a point of reference.

5.2.2. Bald Eagle Lake

Curly-leaf pondweed (CLP) and Eurasian watermilfoil (EWM) became a nuisance for boat navigation and overall lake enjoyment following a second alum application in 2016. CLP treatment areas have increased every year since the 2nd alum treatment was performed in 2016. During this same period, the percentage of points with native taxa and the mean number of native submersed taxa per sampling point have remained similar to pretreatment conditions. Given the percentage of points with native submersed taxa has not increased, despite an increase in water clarity and associated littoral zone expansion, the assumption becomes that there are new, uncolonized areas within the lakes' littoral zone that may are open to infiltration by invasives species.

Table 13. Summary of aquatic submersed plants in Bald Eagle Lake, Ramsey County (DOW# 62000200) as indicated by results of point- intercept surveys. Source: Bald Eagle Lake 2021 Aquatic Vegetation Report.

YEAR	Treatment Date	CLP* Acres Treated	PI Survey Date	Max Depth of Growth in feet [95%]†	% Points w/ Native Submersed Taxa	Mean Native Submersed Taxa/ Point	# Submersed Taxa	AVG Secchi Depth [m]
2010	**APR**	241	**AUG**	11	74	1.6	11	1.6
2011	**MAY**	125	**AUG**	13	71	1.4	13	2.0
2012	**MAY**	97	**AUG**	11	54	0.9	13	1.3
2013	**MAY**	62.5	**-**	-	-	-	-	2.0
2014	**MAY**	92	**SEPT**	10	59	1.5	15	2.0
2015	**MAY**	92	**SEPT**	13	50	1.3	16	3.1
2016	**APR**	14	**AUG**	14	77	2.1	16	2.7
2017	**APR**	28.5	**SEPT**	12	67	1.9	18	NA
2018	**MAY**	19.6	**AUG**	12	71	1.4	16	2.6
2019	**MAY**	68.9	**SEPT**	9	55	1.5	19	2.5
2020	**MAY**	75.5	**AUG**	10	65	1.7	16	2.6
2021	**MAY**	86.9	**SEPT**	9	57	1.6	16	NA

5.2.3. Upper Prior/ Spring Lake

As another example, shifts in aquatic plant growth following alum treatment at Spring Lake in Scott County, Minnesota, have been less drastic but still notable. Improvements in secchi disk depth to above state standards correspond to an increase in maximum depth of aquatic plant growth from 9 feet to 12 feet over several years (McComas, 2021). Unfortunately, 2021 was the largest treatment area of CLP on record from 2014-2021 following the 2020 alum treatment. Also in 2021, Spring Lake had it's first EWM siting and consequently treated 8 acres. Furthermore, the percent coverage of plants has increased from 9% to 30%, largely due to an increase in the Frequency of Occurrence Eurasian watermilfoil.

Table 14. Upper Prior Lake aquatic plant point intercept survey results from 2015, 2018, 2020, and 2021. Source: McComas, 2021

Upper Prior	**Occurrence of Plants**			
	2015	**2018**	**2020**	**2021**
Coontail (*Ceratophyllum demersum*)	5	29	33	25
Elodea *(Elodea canadensis)*	2	17	3	2
Bearded stonewort (*Lychnothamnus barbatus*				1
Northern Watermilfoil *(Myriophyllum sibiricum)*			6	1
Eurasian watermilfoil (*M. spicatum*)	11	17	5	25
Naiads (*Najas flexilis*)		4		2
Curlyleaf pondweed (*Potamogeton crispus*)			3	3
Stringy pondweed (*P. filiformis*)				9
Stringy pondweed (*P. sp*)		2	2	
Sago pondweed *(Stuckenia pectinata)*	2	1		2
Number of submerged species	4	6	6	9
Estimated aquatic plant coverage (ac)	33 ac	74 ac	82 ac	116 ac
Max depth of vegetation (ft)	6 ft	8 ft	10 ft	11 ft
Percent coverage of plants (%)	9%	19%	21%	30%

5.2.4. Balsam Lake, Polk County, Wisconsin

The Balsam Lake Protection and Rehabilitation District (BLPRD) conducted a post-treatment CLP turion survey following a two year pause without chemical control (2018-2019) that saw turion umbers increase in all areas of East Balsam relative to a posttreatment survey conducted in 2017. Subsequently, BLPRD decided to treat 15.6 acres in the Spring of 2020 with an herbicide. The BLPRD conducted an alum treatment in June 2020. Mean (July-September) surface total P was only 31 µg/L (53% reduction over the pre-treatment average), mean chlorophyll was 16.3 µg/L (72% reduction), and mean Secchi transparency was 6.3 ft. (86% improvement) in 2020. Thirty-nine (39) native index species were observed during the August (post-treatment) 2020 survey, a slight improvement from 37 in both 2014 and 2009.

A June 2020 posttreatment survey found declines in the abundance of CLP turions, providing evidence to suggest that a targeted CLP treatment conducted prior to an alum treatment can reduce the number of viable turions available for reproduction in the following spring. However, significant changes in the native plant community were observed in Balsam Lake that appear to be an unintended negative result of herbicide treatments to control curly leaf pondweed.

As a result, the BLPRD purchased a mechanical harvester in 2017 and has elected to use mechanical harvesting to target CLP stands smaller than 25 acres in size. Concentration exposure time (CET) testing has shown that herbicides applied at a small scale (defined as less than 10 acres or 10% of the waterbody) in aquatic environments dissipate quickly and therefore, the efficacy of these small-scale treatments can be unpredictable and difficult to maintain. As a result, small beds have not been treated with an herbicide since 2013. These areas are now being targeted using mechanical harvesting.

5.3. CLP Impacts on Water Quality

Increased aquatic plant coverage and density at Forest Lake has implications for water quality, management costs, recreation, and various other ecosystem functions. CLP contributes to the internal load of the lake during the mid-summer die back (senescence) when the nutrients tied up in CLP biomass are released. The precise contribution may be widely variable and is not known for Forest Lake (Heiskary & Valley, 2012). For a point of reference, a 2011 TMDL study of Crystal, Keller, and Lee Lake found that CLP senescence contributed approximately 1.09 pound of phosphorus per acre annually. In other Minnesota Lakes, CLP senescence has been reported to contribute as much as 5 pounds of phosphorus per acre, annually (Steve McComas, Bluewater Science).

5.3.1. Case Study: Jefferson German Chain – Mankato, Minnesota

In 2010 and 2011, Joe Pallardy harvested and analyzed aquatic plant material monthly from the Jefferson-German Chain (JGC) located in southern Minnesota. The following bullet points provide insight into how CLP senescence might impact water quality.

- The mean CLP total phosphorus (TP) concentration observed in CLP samples collected in May was significantly greater than the mean TP found from CLP samples collected in June ($P < 0.001$). In May, CLP had a mean TP concentration of 9.7 mg/g dry plant tissue (SE = 1.4) and in June, the mean TP concentration of CLP was 4.2 mg/g dry plant tissue (SE = 0.5; Figure 15).
- Total phosphorus lost via CLP senescence was not immediately returned to the sediment as there was no difference in the mean TP concentration of sediment samples among months (May through July, 2010; P = 0.492).

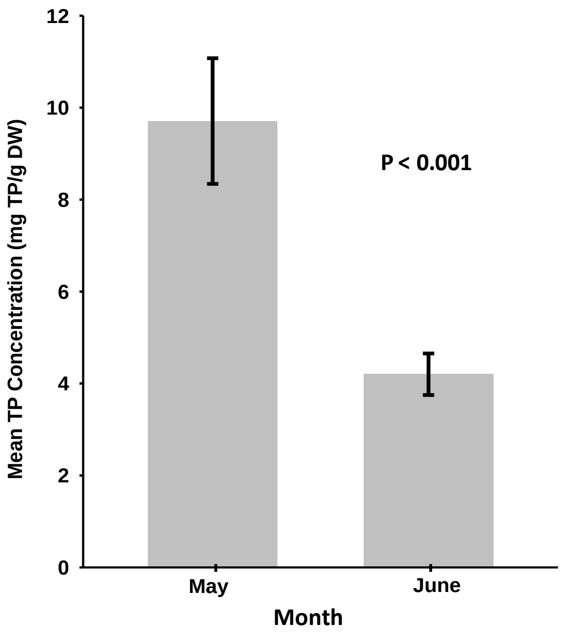


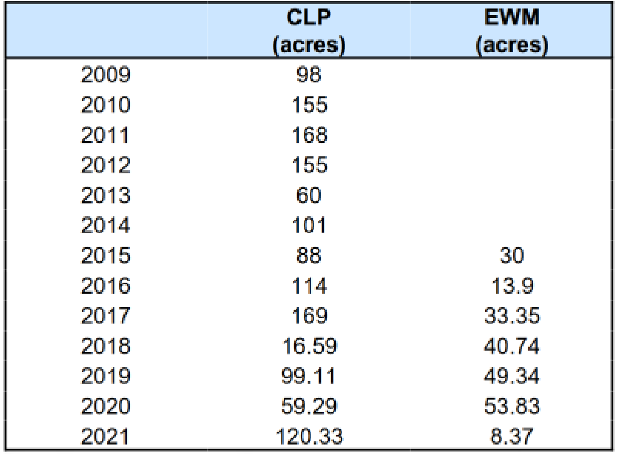
Figure 15. The mean total phosphorus (TP) concentration of CLP samples [mg TP/g dry weight (DW)] collected in May and June 2010 from the Jefferson-German Chain. The statistical test P-value is noted and error bars represent ± 1 standard error. N = 25. Source: Joe Pallardy 2012 Thesis Research.

5.4. Implications for Forest Lake

5.4.1. CLP Impacts on Forest Lake Water Quality

Table 15 shows the total area of CLP and EWM treated from 2009-2021. On average, the CLFLWD treated 107 acres per year. Historically the treatments have occurred in May. In 2021, the district treated 120.33 acres with diquat, a contact herbicide on May 25 and 26, 2021. A comparison of average monthly TP concentrations in May vs. June (Figure 16) shows only a slight increase in total phosphorus concentration during June (Post-Treatment). Further, average monthly TP concentrations in June are below the District's 30 ug/L target. Proactively reducing CLP biomass in May appears to be preventing a mid-summer release of phosphorus during July, when CLP naturally senesces. The largest month-by month increase of in-lake TP concentrations occurs in September on the Middle Basin. The month of September is strongly correlated with fall turnover, another indication that internal loading from the Middle Basin's anoxic hypolimnion is a major factor in that basin's water quality.

Table 15. Curly-leaf Pondweed (CLP) and Eurasian Water Milfoil (EWM) Treatment Acres 2009-2021.



	CLP (acres)	EWM (acres)
2009	98	
2010	155	
2011	168	
2012	155	
2013	60	
2014	101	
2015	88	30
2016	114	13.9
2017	169	33.35
2018	16.59	40.74
2019	99.11	49.34
2020	59.29	53.83
2021	120.33	8.37

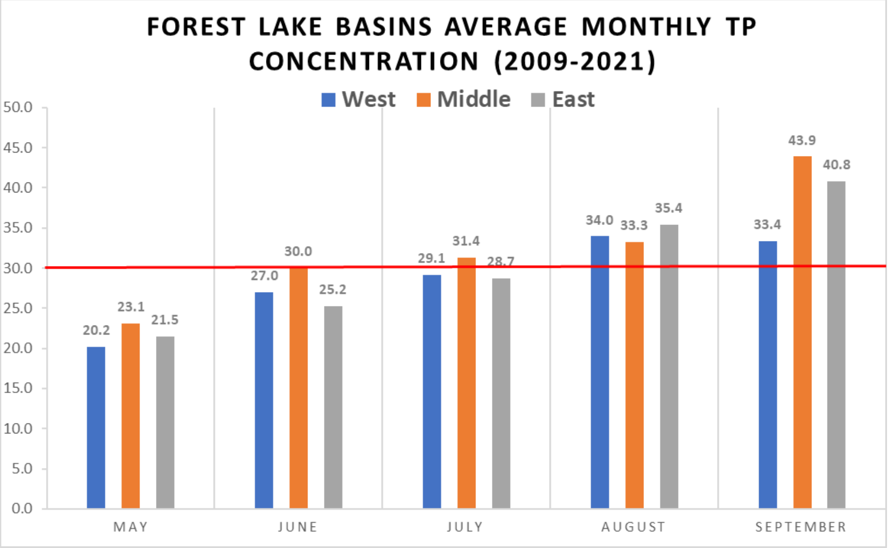


Figure 16. Forest Lake Basins - Average Monthly in-lake Total Phosphorus (TP) concentration (ug/L) relative to the 30 ug/l goal.

5.5. Aquatic Plant Management Recommendations

The District should continue with its existing management practices for CLP with a focus on annual delineation of both CLP and EWM and annual CLP herbicide applications. The Forest Lake Vegetation Management Plan (FLVMP) will explore the positive and negative aspects of implemented aquatic plant management techniques on an annual basis. The FLVMP will establish lake specific aquatic plant management goals that are in line with the District's AIS Management Plan.

The FLVMP will identify quantifiable goals (e.g., Maintain Floristic Quality Index (FQI) score above 25 within areas treated by herbicides) to maintain accountability and to assess the effectiveness of implemented treatment options. It is important to recognize that progress towards improving the quality of an aquatic plant community through the reduction of invasive species like EWM or CLP is often slow. At the same time, operating in a reactionary nature to periodic increases in EWM or CLP abundance is not an ecologically sustainable solution. Rather, the techniques identified in the FLVMP should identify strategies to significantly reduce the abundance of both EWM and CLP with a long-term goal of reducing EWM and CLP abundance below an agreed upon littoral occurrence (e.g., 15% of points sampled) threshold. Once achieved, the primary control measure should evaluate the capacity for the District to move away from herbicides and towards a long-term solution that relies on biological (native plant restoration) and/or physical controls. The CLFLWD will continuously update management strategies by incorporating lessons learned from area lakes and the latest science regarding aquatic plant management.

6. CARP MANAGEMENT

6.1. Common Carp Background

Common carp (*Cyprinus carpio*) are known to uproot aquatic vegetation and stir lake sediments, thereby reducing the density of aquatic vegetation, increasing turbidity, and releasing nutrients back into the water column. The increase in nutrients can lead to algal blooms that decrease water clarity, further reducing the aquatic vegetation community. Research at the University of Minnesota has indicated that carp densities of 100 lb/acre or more can have a significant impact on the native vegetation community, and that a density of 30 lb/acre may be a more appropriate target for lake management (Bajer, Sullivan, & Sorensen, 2009). In addition, high concentrations of carp have been shown to cause significant water quality issues in lake environments. By managing at a lower level, even if carp can spawn successfully, early detection of increased carp recruitment will provide managers with an opportunity to proactively reduce carp biomass before it negatively effects water quality.

6.1.1. CLFLWD Goal Statement

Item 3011H of the CLFLWD 2022-2031 Watershed Management Plan states:

> *The District will remove common carp to protect native aquatic plants, limit resuspension of lake bottom materials, and reduce internal phosphorus load in District lakes. Common carp harvests will be conducted in District lakes to decrease the common carp population to a level that does not detrimentally impact the lake water quality. In order to accurately assess the biomass of common carp in District lakes, fish population surveys and/or assessments will be*

performed as needed. Several different fish surveying techniques will be considered based on specific needs including but not limited to standard fyke net, mini-fyke net, seining, and electrofishing.

6.1.2. Carp Population Assessment

The CLFLWD coordinates with the MN Department of Natural Resources' timeline for conducting fish surveys to prevent duplication of efforts. Fisheries data collected to date provides evidence to suggest that carp densities in Forest Lake are below the 100 kg/ha threshold; however, an exact population estimate has not been determined. The most recent fisheries survey of Forest Lake was completed on 7/5/2021. Common carp catch per unit effort (CPUE) was low, relative to the abundance of native gamefish species. In total, only 3 common carp were captured during the 2021 survey.

6.1.3. Carp Management Efforts

EOR's recommendations for carp management on Forest Lake are consistent with management activities currently planned as part of the District's ongoing AIS Prevention and Management Plan (2021). Largely, carp management activities in the Forest Lake Management District are focused on reducing carp abundance in upstream lakes and connected streams, primarily Shields Lake. The following paragraphs summarize carp management practices that have taken place thus far in the Forest Lake Management District as well as the current research and best practices for carp management gleaned from local and regional studies.

Carp Barriers

The CLFLWD owns and operates two fish barriers associated with Forest Lake. The electric fish barrier located on the tributary between Shields Lake and Forest Lake, was augmented in 2020 with a passive, mechanical fish barrier. The new barrier will result in long-term cost savings due to lower ongoing operations and maintenance costs. In February 2021, the District repaired the fish barrier on the northwest side of Forest Lake, where the lake outlets to the Sunrise River. The fish barrier is designed to limit the ability for carp and other rough fish from migrating into Forest Lake from the Sunrise River.

Carp Removal

The CLFLWD has attempted several carp removals in Shields Lake in 2019 and 2020 to reduce the carp population. A common carp removal was attempted in the Fall of 2019, resulting in lower-than-expected removal numbers. According to WSB's "Shields Lake: 2019 Carp Removal Project Report" there are still between 364 and 630 individual carp that need to be removed from the lake in order to reach management goals. In 2020, the CLFLWD implemented an experimental carp removal project which ultimately failed. Currently, CLFLWD staff are considering using bow-anglers to help remove carp, which would minimize lake bottom sediment disturbance following an alum treatment.

6.1.4. Spawning Habitat Assessment

Common carp prefer to spawn in shallow, weedy bays of lakes with silty substrate and/or connected wetlands with submergent vegetation or inundated terrestrial vegetation at water depths less than 0.5 meters (approximately 2 feet). Marginal spawning occurs in water up to 1.8 meters (6 feet) deep (McCrimmon 1968). Large, shallow lakes or lakes with large shallow bays provide optimum in-lake spawning grounds for carp. Research conducted in Australia in 2008 found that carp are positively rheotactic which is another way of stating that carp tend to concentrate in large masses in areas with flowing water such as lake inflow and outflow points; especially during the spawning season. Telemetry data has suggested that while carp overwinter in deep lakes that don’t winterkill, they tend to travel to winter-kill prone shallow lakes and wetlands to spawn. This behavior presumably takes advantage of a lack of predators in the shallow lakes and wetlands due to winterkill of predatory species such as bluegill (*Lepomis machrochirus*) (Bajer and Sorenson, 2010).

An aerial photo collected at the Linn Lake outlet to South Center Lake in Chisago County, Minnesota in 2014 provides a critical demonstration of the potential role of connected inflow points in terms of their capacity to attract carp (Figure 17). Figure 18 identifies potentially suitable in-lake carp spawning areas within Forest Lake. Table 16. Percentage of Lake Area Within Preferred Spawning Depths highlights the percent of the total lake area suitable as carp spawning habitat. Telemetry data collected from Minnesota Lakes suggests that shallow bays near inflow/outflow points from connected wetlands, streams, or lakes represent the most likely suitable locations for capturing carp during the spring spawning season.

Table 16. Percentage of Lake Area Within Preferred Spawning Depths

Lake Name	0-5 ft. (Preferred)	5-10 ft. (Marginal)	>10 feet
Forest Lake	30%	19%	51%

Based on DNR bathymetry-not reflecting water level fluctuations.

White Outline = Large aggregation of carp attracted to Linn Lake Outflow.

Flowing water from Linn Lake outlet during high water

Figure 17. Congregation of carp at Linn Lake Outlet in 2014.

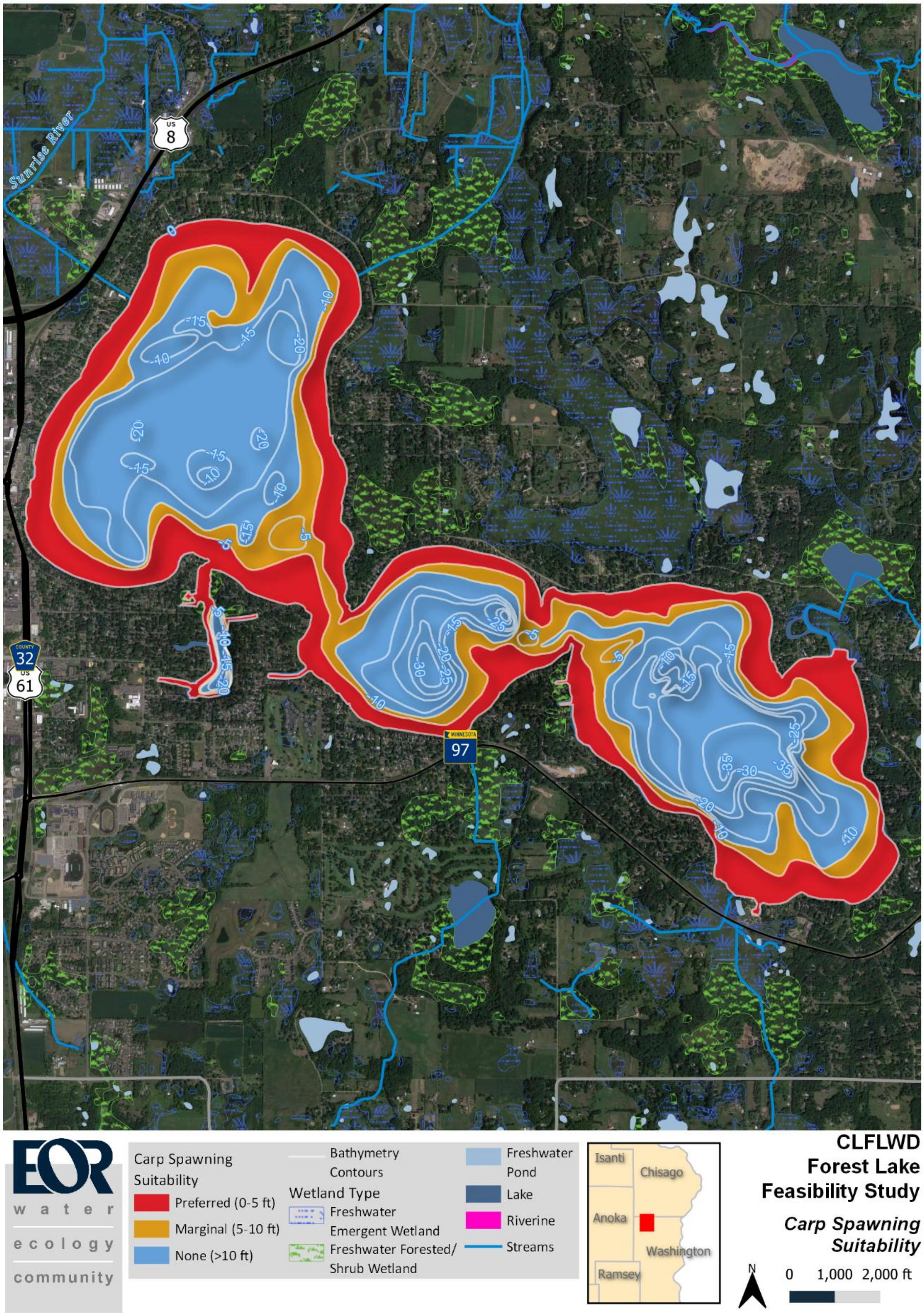


Figure 18. Red areas indicate preferred in-lake carp spawning areas. Connected streams and wetlands provide additional, suitable carp spawning habitat.

6.1.5. Carp Management Recommendation

The CLFLWD has identified a goal of removing common carp to protect native aquatic plants, limit resuspension of lake bottom materials, and reduce internal phosphorus load in District lakes. While carp populations have not officially been determined for Forest Lake, fisheries data collected to date provides evidence to suggest that carp populations are below the 30 kg/ha threshold.

To accurately assess the biomass of common carp in Forest Lake, focused carp population surveys and/or assessments should be performed in 2023 and again in 2027 and in any connected waterbody where carp may spawn and then migrate to Forest Lake. Several different fish surveying techniques will be considered based on specific needs including but not limited to standard fyke net, mini-fyke net, seining, and electrofishing.

6.1.6. Other Carp Management Options (not recommended at this time)

Winter Seining

Winter seining operations conducted on the Riley Chain of Lakes demonstrated the potential effectiveness of winter seining operations with over 80% of adult carp removed from each of the three lakes targeted (Bajer et al., 2010). Despite the potential effectiveness of these seining operations, methods for controlling future carp recruitment must remain a top priority given that a single female carp can carry over 1 million eggs. Juvenile carp grow fast and can quickly reach sizes that prohibit control by native piscivores (fish that consume other fish). The explosive population growth of this species can quickly negate dollars spent towards harvesting efforts.

Fish Stocking

Recent research conducted in Minnesota, has found that bluegills (*Lepomis machrochirus*) are capable of completely suppressing carp recruitment so long as sufficient concentrations of oxygen exist to prevent winterkill in connected bays and wetlands. Therefore, the number one priority in controlling future common carp recruitment, should future carp population surveys indicate a need to do so, is identifying hydrologically connected bays, wetlands, and shallow riverine marshes prone to winterkill (Bajer et al., 2014). Figure 18 shows the potential locations of these areas. A survey identifying additional hydrologically connected wetlands, ponds or other basins subject to winterkill is recommended to identify additional areas where migration barriers or fish stocking may be needed.

7. SUMMARY OF FINDINGS

Analyses completed as part of this study included **a**) analysis of 11 lake sediment cores by Professor Bill James at the University of Wisconsin-Stout Center for Limnological Research and Rehabilitation and **b**) review of current and historic fisheries surveys (carp population numbers) and aquatic vegetation surveys to determine appropriate fish and aquatic plant management techniques.

We identified the following combined approach of three management activities to be the most practical and cost-effective way to address internal phosphorus loading to Forest Lake:

7.1. Recommended Management Approach

We identified the following combined approach of three management activities to be the most practical and cost-effective way to address internal phosphorus loading to Forest Lake:

1. **In-Lake Alum Treatment:** Conduct an alum treatment of the Middle Basin. We recommend splitting the total alum dosage into two separate applications. The initial dosing of the Middle Basin would occur in Summer/Fall of 2023 and the second one in the Summer/Fall 2025. Consistent with the District's Adaptive Management philosophy, delaying the second dosing until 2025 would allow for the ability to assess the effectiveness of the first treatment and design the second treatment (if needed) in a more accurate, cost-effective way. An alum treatment of the West Basin and East basin is not recommended at this time, however using the District's adaptive approach an alum dosing on the East basin could be considered in the future if further water quality improvements are still needed based on the ongoing data collection that will continue on Forest Lake
2. **Vegetation Management:**
    a. Continued baseline management of curly-leaf pondweed (CLP) and continue to conduct aquatic plant surveys to minimize expansion of invasives and allow natives to establish in shallow areas using targeted herbicide.

    b. Create and maintain a dynamic (living) vegetation management plan that seeks to continuously evaluate and incorporate the latest aquatic plant management practices. The Forest Lake Vegetation Management Plan (FLVMP) will build upon the annual pre-treatment and post-treatment survey work already being completed by Blue Water Science. Further, the LVMP will explore the positive and negative aspects of various aquatic plant management techniques and establish lake specific aquatic plant management goals that are in line with the District's 2021 AIS Prevention and Management Plan.
3. **Carp Management:**
    a. Conduct a focused population survey to validate carp populations remain below 30 lb./acre. The fishery survey should include a population assessment of adjacent wetlands and streams that may provide additional spawning habitat.

b. Maintain carp abundance below 30 lb./acre by identifying opportunities to prevent carp from migrating to adjacent waterbodies.

c. Maintaining a healthy native gamefish community should organically prevent carp from exceeding the 30 lb./acre threshold.

7.1.1. Goal Statement

The goal behind the implementation of the proposed management activities is to achieve the internal load reductions needed for Forest Lake to achieve a long-term, five-year average summer phosphorus concentration at or below 30 ppb as identified in the CLFLWD 2012-2021 Watershed Management Plan. Rather than focusing on a targeted hypolimnion phosphorus concentration, the focus should be on the practices that will reduce sediment phosphorus release rates in both the anoxic and oxic portions of each basin.

In-lake management activities will begin with a split dose alum application to bind RP in the portions of the Middle Basin that are greater than 15 feet deep. Once RP in the water column has been reduced and lake clarity improves, the density and distribution of submergent vegetation will increase. In 2023, the CLFLWD will develop and maintain a proactive lake vegetation management plan for Forest Lake that will explore the positive and negative aspects of various aquatic plant management techniques and establish lake specific aquatic plant management goals that are in line with the District's AIS Management Plan.

The District has already achieved over 80% of the external load reduction goal for Forest Lake. Adoption of the in-lake management plan would be expected to achieve all the internal load reductions needed to reach the 30 ug/L goal for each basin.

The management activities of the treatment plan with associated timing and costs are presented in Table 17 below. As these management activities are undertaken iteratively, an adaptive management approach may allow to forego some proposed activities/costs.

Table 17. Recommended Management Plan Activities

Management Activity	2023		2024		2025	2026	2027
	Fall '22 - Spring '23	Summer Fall	Fall '23 - Spring '24	Summer Fall			
Alum treatments (Middle Basin)[1]		**$280,000**			**$310,000**		
Baseline invasive plant management[2]		**$35,000**		**$37,000**	**$40,000**	**$43,000**	**$25,000**
Create/ Maintain a Lake Vegetation Management Plan		**$15,000**			**$5,000**		**$5,000**
Conduct focused fisheries survey to validate carp populations		**$10,000**					**$6,000**
Total	**$0**	**$340,000**	**$0**	**$37,000**	**$355,000**	**$43,000**	**$36,000**
						Grand Total	**$811,000**

[1] Two alum doses at $280,000 and $310,000 each. A range of costs for the alum dosing application materials and labor are shown in Table 2. Costs are based on a cost of $1.93 per gallon of alum applied (Personal Communication, John Holz). The costs presented do not include administration, design, permitting, or other management costs.

[2] Cost represents treatment of CLP up to 120 acres (specific area size to be determined annually) and includes Blue Water Science Survey

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