2025

PAW PAW LAKE
DREDGING/ALUM FEASIBILITY STUDY

PREPARED FOR:
COLOMA AND WATERVLIET CHARTER TOWNSHIPS
BERRIEN COUNTY, MI

PROGRESSIVE COMPANIES

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EXECUTIVE SUMMARY

The Paw Paw Lake Special Assessment Districts (SAD) in both Watervliet Charter Township and Coloma Charter Township were originally formed in 2011 to manage conditions in Paw Paw Lake. In June of 2024, public hearings were held and both townships approved the continuation of the project for a four-year period. At the public hearings, a comprehensive dredging and alum (aluminum sulfate) feasibility study was also approved. The following is a summary of the study:

<u>Water Quality Sampling:</u> In 2024, extensive sampling was conducted at the three deep basins of Paw Paw Lake in March, July, August, September, and October. Sampling was intentionally timed to document the development of the thermocline over the season and the resultant loss of oxygen below the thermocline as the season progressed. The thermocline did show a normal downward progression as expected over the summer and fall with the thermocline occurring at around a depth of 18 feet in July and slowly progressing towards a maximum depth of about 35 feet in October. However, the expected increase in soluble reactive phosphorus below the thermocline did not occur until around a depth of 40 feet during all of the sampling periods at all three sites. These data suggest that managing the high soluble reactive phosphorus (available phosphorus for use by migratory algae) should focus on the depths of 40 feet and below, and not the entire hypolimnion (zone below the thermocline). This concentration of resources would result in substantial savings no matter what phosphorus mitigation strategy is pursued. Options for phosphorus mitigation studied in this report include an alum treatment and/or hypolimnetic (deep-water) oxygenation. Cost estimates for each option are provided in this report. Other options for phosphorus mitigation and/or algae control are being explored but are outside of the context of this report.

<u>Sediment Core Sampling Results:</u> On October 21, 2024 staff from Barr Engineering and Progressive Companies collected sediment cores from a total of 8 different sites in a longitudinal orientation from southwest to northeast across the deepest portions of Paw Paw Lake using a gravity coring device. Samples were placed on ice and delivered intact to Barr's laboratory in Minneapolis, MN. Each core was then sectioned vertically and analyzed to determine relative composition of various sediment phosphorus fractions by depth below the sediment-water interface. In addition, the three deep basin samples were incubated in the laboratory to simulate redox (oxygen-free) conditions. Three different methods were then used to calculate potential phosphorus release from the sediments and results were compared. Comparison of data suggests that the northeast basin contributes the highest relative redox phosphorus followed by the central basin and to a much lesser degree, the southwest basin. It is recommended that phosphorus mitigation efforts should focus on the northeast basin and the central basin at depths below 40 feet.

<u>Dredging Estimates:</u>
This study assessed the need for dredging three channels on Paw Paw Lake: the Lake Stella connector, the Branch/Derby inlet, and the Elm Drive channel. The Branch/Derby and Elm Drive channels were found to have adequate water depths for navigation and do not currently require dredging. In contrast, the Lake Stella channel showed significant sediment accumulation and shallow depths, suggesting dredging from Paw Paw Lake to about half way up the channel could improve navigability. Approximately 1,222 cubic yards of sediment would need to be removed, with estimated costs ranging from $105,000 to $250,000 depending on sediment conditions and disposal requirements. If dredging is pursued, a more extensive study would be required to asses goals, Michigan Department of Environment, Great Lakes, and Energy (EGLE) permit requirements, disposal options, environmental impacts, and costs.

INTRODUCTION

Paw Paw Lake is a 922-acre deep lake located in Berrien County, Michigan with an average depth of 32 feet and a residence time of 776 days. Historic water quality monitoring data shows high levels of total phosphorus in the hypolimnion, with some values exceeding 375 µg/L (micrograms per liter or parts per billion) at deep, oxygen-depleted sampling points. This internal loading of phosphorus contributes to excessive growth of aquatic plants and algae, accelerating the eutrophication—or ecological aging—of Paw Paw Lake.

This study aims to quantify organic sediment accumulation and internal phosphorus loading/bio-availability in order to evaluate the necessity and feasibility of canal dredging for improved navigation and aluminum sulfate (alum) application to reduce internal phosphorus loading in targeted areas of Paw Paw Lake. As part of this effort, the lake's physical, chemical, and biological characteristics were examined through monthly water quality sampling during thermal stratification, a canal sediment depth assessment, and a lake sediment study conducted by Barr Engineering to estimate internal phosphorus release rates and determine appropriate mitigation options.

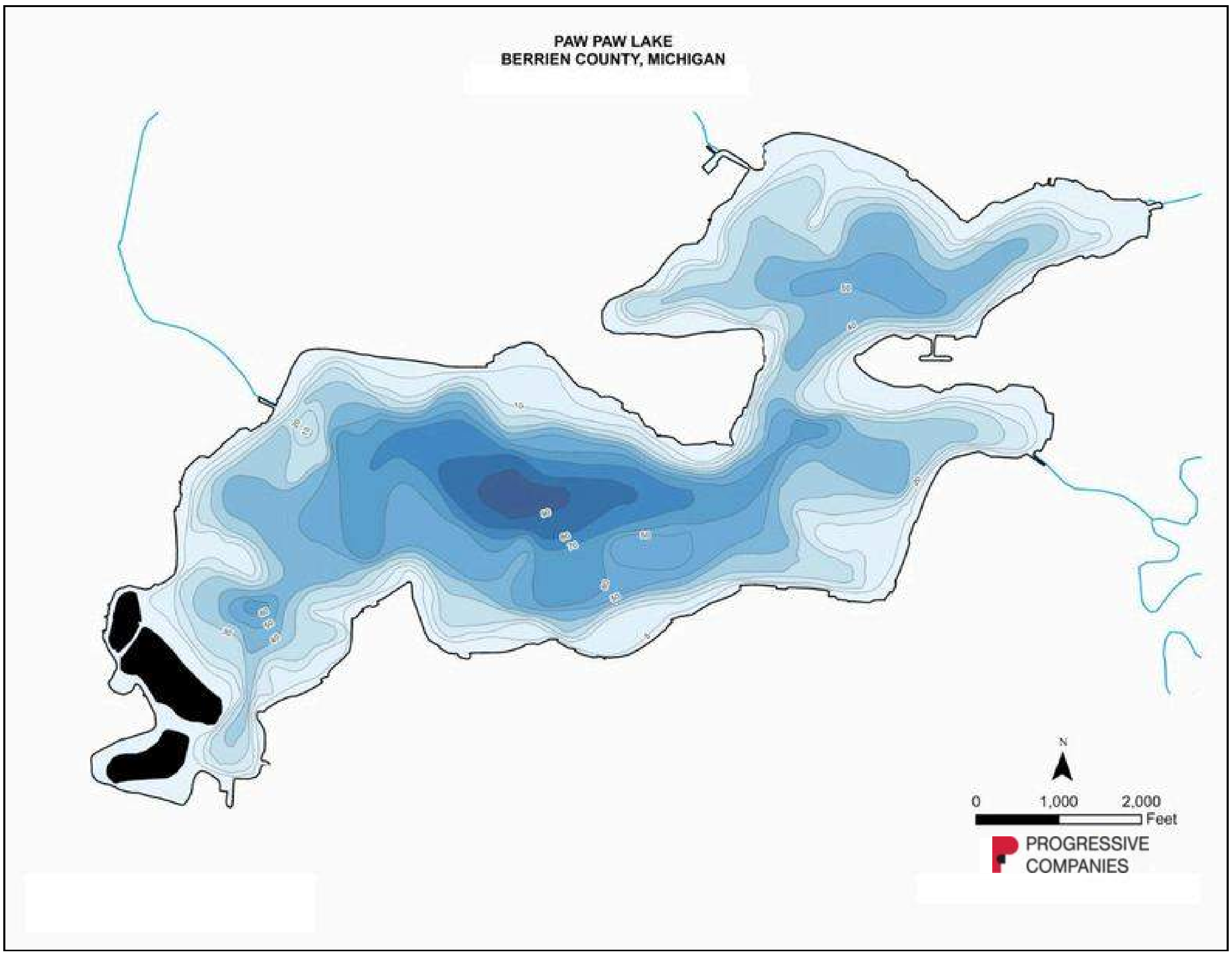

Figure 1. Paw Paw Lake Depth Contour Map

PHYISCAL CHARACTERISTICS

Paw Paw Lake encompasses a surface area of 922 acres and has a maximum depth of 90 feet, with an average depth of 32.2 feet. The lake holds an estimated volume of 29,645 acre-feet, reflecting substantial water storage capacity. Paw Paw Lakes water residence time is approximately 776 days (a little over two years). Water residence time is the amount of time it takes to completely replenish the total volume of water in the lake and is also referred to as “turnover time.” Paw Paw Lake’s shoreline extends approximately 12.1 miles, and the shoreline development factor is calculated at 2.8, indicating a moderately irregular perimeter with numerous coves and canals. These physical characteristics—such as depth, volume, lake residence time, and shoreline complexity—directly influence water circulation, sediment deposition, and nutrient dynamics, particularly internal phosphorus loading. As a result, they are important variables in evaluating the potential effectiveness and necessity of management interventions such as dredging and alum treatment.

TABLE 1 - PAW PAW LAKE PHYSICAL CHARACTERISTICS

Lake Surface Area	**922 Acres**
Maximum Depth	**90 Acres**
Mean Depth	**32.2 Feet**
Lake Volume	**29,645 Acre-feet**
Shoreline Length	**12.1 miles**
Shoreline Development Factor	**2.8**
Residence Time	**776 Days**

WATER QUALITY

LAKE WATER QUALITY

Lake water quality is determined by a unique combination of processes that occur both within and outside of the lake. In order to make sound management decisions, it is necessary to have an understanding of the current physical, chemical, and biological condition of the lake, and the potential impact of drainage from the surrounding watershed.

Lakes are commonly classified as oligotrophic, mesotrophic, or eutrophic (Figure 2). Oligotrophic lakes are generally deep and clear with little aquatic plant growth. These lakes maintain sufficient dissolved oxygen in the cool, deep bottom waters during late summer to support cold-water fish such as trout and whitefish. By contrast, eutrophic lakes are generally shallow, turbid, and support abundant aquatic plant growth. In deep eutrophic lakes, the cool bottom waters usually contain little or no dissolved oxygen. Therefore, these lakes can only support warmwater fish such as bass and pike. Lakes that fall between these two extremes are called mesotrophic lakes.

Under natural conditions, most lakes will ultimately evolve to a eutrophic state as they gradually fill with sediment and organic matter transported to the lake from the surrounding watershed. As the lake becomes shallower, the process accelerates. When aquatic plants become abundant, the lake slowly begins to fill in as sediment and decaying plant matter accumulate on the lake bottom. Eventually, terrestrial plants become established and the lake is transformed to a marshland. The aging process in lakes is called "eutrophication" and may take anywhere from a few hundred to several thousand years, generally depending on the size of the lake and its watershed. The natural lake aging process can be greatly accelerated if excessive amounts of sediment and nutrients (which stimulate aquatic plant growth) enter the lake from the surrounding watershed. Because these added inputs are usually associated with human activity, this accelerated lake aging process is often referred to as "cultural eutrophication." The problem of cultural eutrophication can be managed by identifying sources of sediment and nutrient loading (i.e., inputs) to the lake and developing strategies to halt or slow the inputs. Thus, in developing a management plan, it is necessary to determine the limnological (i.e., the physical, chemical, and biological) condition of the lake and the physical characteristics of the watershed as well. Key parameters used to evaluate the limnological condition of a lake include temperature, dissolved oxygen, total phosphorus, pH and alkalinity, chlorophyll-*a*, and Secchi transparency.

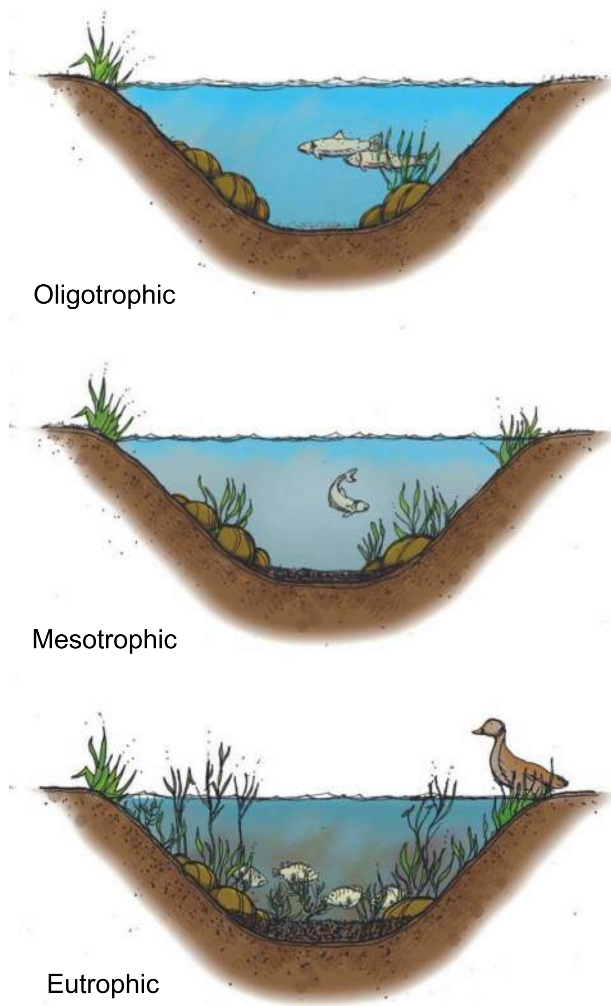

Figure 2. Lake classification

TEMPERATURE
Temperature is important in determining the type of organisms which may live in a lake. For example, trout prefer temperatures below 68°F. Temperature also determines how water mixes in a lake. As the ice cover breaks up on a lake in the spring, the water temperature becomes uniform from the surface to the bottom. This period is referred to as "spring turnover" because water mixes throughout the entire water column. As the surface waters warm, they are underlain by a colder, more dense strata of water. This process is called thermal stratification (Figure 3). Once thermal stratification occurs, there is little mixing of the warm surface waters with the cooler bottom waters. The transition layer that separates these layers is referred to as the "thermocline." The thermocline is characterized as the zone where temperature drops rapidly with depth. As fall approaches, the warm surface waters begin to cool and become more dense. Eventually, the surface temperature drops to a point that allows the lake to undergo complete mixing. This period is referred to as "fall turnover." As the season progresses and ice begins to form on the lake, the lake may stratify again. However, during winter stratification, the surface waters (at or near 32°F) are underlain by slightly warmer water (about 39°F). This is sometimes referred to as "inverse stratification" and occurs because water is most dense at a temperature of about 39°F. As the lake ice melts in the spring, these stratification cycles are repeated.

DISSOLVED OXYGEN
An important factor influencing lake water quality is the quantity of dissolved oxygen in the water column. The major inputs of dissolved oxygen to lakes are the atmosphere and photosynthetic activity by aquatic plants. An oxygen level of about 5 mg/L (milligrams per liter, or parts per million) is required to support warmwater fish. In lakes deep enough to exhibit thermal stratification, oxygen levels are often reduced or depleted below the thermocline once the lake has stratified. This is because the oxygen has been consumed, in large part, by bacteria that use oxygen as they decompose organic matter (plant and animal remains) at the bottom of the lake. Bottom-water oxygen depletion is a common occurrence in eutrophic and some mesotrophic lakes. Thus, eutrophic and most mesotrophic lakes cannot support coldwater fish because the cool, deep water (that the fish require to live) does not contain sufficient oxygen.

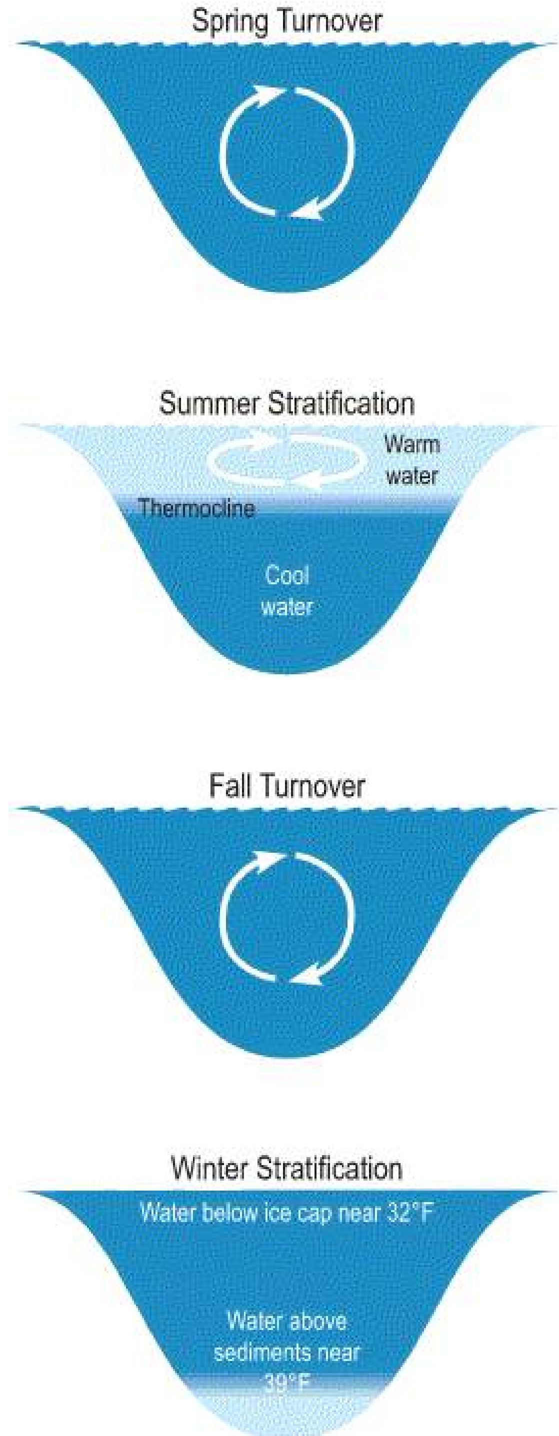

Figure 3. Seasonal thermal stratification cycles

PHOSPHORUS

The quantity of phosphorus present in the water column is especially important since phosphorus is the nutrient that most often controls aquatic plant growth and the rate at which a lake ages and becomes more eutrophic. By reducing the availability of phosphorus in a lake, it is often possible to control the amount of aquatic plant growth. In general, lakes with a total phosphorus concentration of 20 μg/L or greater are can support abundant plant growth and are classified as eutrophic.

Phosphorus enters the lake either from the surrounding watershed, or from the sediments in the lake itself, or both. The input of phosphorus from the watershed is called "external loading," and from the sediments is called "internal loading." External loading occurs when phosphorus washes into the lake from sources such as fertilizers, septic systems, and eroding land. Internal loading occurs when bottom-water oxygen is depleted, resulting in a chemical change in the water near the sediments. The chemical change causes phosphorus to be released from the sediments into the lake where it becomes available as a nutrient for aquatic plants.

In lake ecology, phosphorus is most commonly measured in and represented by total phosphorus. This study includes measurements of soluble reactive phosphorus, or dissolved inorganic phosphorus, which is the form of phosphorus that is readily available for use by plants and algae. Since soluble reactive phosphorus is a portion of total phosphorus, its concentration is typically lower. However, the same benchmark of 20 μg/L can be used to indicate eutrophic conditions.

CHLOROPHYLL-*a*

Chlorophyll-*a* is a pigment that imparts the green color to plants and algae. A rough estimate of the quantity of algae present in lake water can be made by measuring the amount of chlorophyll-*a* in the water column. A chlorophyll-*a* concentration greater than 6 μg/L is considered characteristic of a eutrophic condition.

SECCHI TRANSPARENCY

A Secchi disk is often used to estimate water clarity. The measurement is made by fastening a round, black and white, 8-inch disk to a calibrated line (Figure 4). The disk is lowered over the deepest point of the lake until it is no longer visible, and the depth is noted. The disk is then raised until it reappears. The average between these two depths is the Secchi transparency. Generally, it has been found that aquatic plants can grow at a depth of at least twice the Secchi transparency measurement. In eutrophic lakes, water clarity is often reduced by algae growth in the water column, and Secchi disk readings of 7.5 feet or less are common.

Figure 4. Secchi disk

LAKE CLASSIFICATION CRITERIA

Ordinarily, as phosphorus inputs (both internal and external) to a lake increase, the amount of algae the lake can support will also increase. Thus, the lake will exhibit increased chlorophyll-*a* levels and decreased transparency. A summary of lake classification criteria developed by the Michigan Department of Natural Resources is shown in Table 2.

TABLE 2 - LAKE CLASSIFICATION CRITERIA

Lake Classification	Total Phosphorus (μg/L)*	Chlorophyll-*a* (μg/L)*	Secchi Transparency (feet)
Oligotrophic	Less than 10	Less than 2.2	Greater than 15.0
Mesotrophic	10 to 20	2.2 to 6.0	7.5 to 15.0
Eutrophic	Greater than 20	Greater than 6.0	Less than 7.5

* μg/L = micrograms per liter

pH and TOTAL ALKALINITY

pH is a measure of the amount of acid or base in the water. The pH scale ranges from 0 (acidic) to 14 (alkaline or basic) with neutrality at 7. The pH of most lakes in the Upper Midwest ranges from 6.5 to 9.0 (Michigan Department of Environmental Quality (Michigan Department of Environmental Quality, 2012) (Table 3). In addition, according to EGLE (Michigan Department of Environment, Great Lakes, and Energy, 2021):

While there are natural variations in pH, many pH variations are due to human influences. Fossil fuel combustion products, especially automobile and coal-fired power plant emissions, contain nitrogen oxides and sulfur dioxide, which are converted to nitric acid and sulfuric acid in the atmosphere. When these acids combine with moisture in the atmosphere, they fall to earth as acid rain or acid snow. In some parts of the United States, especially the Northeast, acid rain has resulted in lakes and streams becoming acidic, resulting in conditions which are harmful to aquatic life. The problems associated with acid rain are lessened if limestone is present, since it is alkaline and neutralizes the acidity of the water.

Most aquatic plants and animals are adapted to a specific pH range, and natural populations may be harmed by water that is too acidic or alkaline. Immature stages of aquatic insects and young fish are extremely sensitive to pH values below 5. Even microorganisms which live in the bottom sediment and decompose organic debris cannot live in conditions which are too acidic. In very acidic waters, metals which are normally bound to organic matter and sediment are released into the water. Many of these metals can be toxic to fish and humans. Below a pH of about 4.5, fish are unable to survive. The Michigan Water Quality Standard (Part 4 of Act 451) states that pH shall be maintained within the range of 6.5 to 9.0 in all waters of the state.

Alkalinity, also known as acid-neutralizing capacity or ANC, is the measure of the pH-buffering capacity of water in that it is the quantitative capacity of water to neutralize an acid. pH and alkalinity are closely linked and are greatly impacted by the geology and soil types that underlie a lake and its watershed. According to MDEQ (2012):

Michigan’s dominant limestone geology in the Lower Peninsula and the eastern Upper Peninsula contributes to the vast majority of Michigan lakes being carbonate-bicarbonate dominant [which increases alkalinity and moderates pH] and lakes in the western Upper Peninsula having lower alkalinity and thus lesser buffering capacity.

The alkalinity of most lakes in the Upper Midwest is within the range of 23 to 148 milligrams per liter, or parts per million, as calcium carbonate (Michigan Department of Environmental Quality, 2012) (Table 3).

TABLE 3 - pH AND ALKALINITY OF UPPER MIDWEST LAKES

Measurement	Low	Moderate	High
pH (in standard units)	Less than 6.5	6.5 to 9.0	Greater than 9.0
Total Alkalinity or ANC (in mg/L as $CaCO_3$)*	Less than 23	23 to 148	Greater than 148

* MDEQ now the Michigan Department of Environment, Great Lakes, and Energy
* mg/L as $CaCO_3$ = milligrams per liter as calcium carbonate

CHLORIDE

Normally, chloride is a very minor component of freshwater systems and background concentrations are generally less than about 10 mg/L (Wetzel, 2001; Fuller and Taricska, 2012) (Figure 5). However, chloride pollution from sources such as road salting, industrial or municipal wastewater, water softeners, and septic systems can increase chloride levels in lakes. Increased chloride levels can reduce biological diversity and, because chloride increases the density of water, elevated chloride levels can prevent a lake from completely mixing during spring and fall (Figure 6). The U.S. Environmental Protection Agency's acute and chronic standards for protection of freshwater aquatic life are 860 and 230 mg/L of chloride, respectively (U.S. Environmental Protection Agency [EPA], 2021). EPA states that "[a]quatic life criteria for toxic chemicals are the highest concentration of specific pollutants or parameters in water that are not expected to pose a significant risk to the majority of species in a given environment or a narrative description of the desired conditions of a water body being 'free from' certain negative conditions."

In 2019, EGLE established water quality values for chloride to describe the impacts to aquatic life. EGLE set the final chronic value (FCV) for chloride at 150 mg/L, stating that long-term exposure above this concentration can be harmful to aquatic life such as fish and invertebrates (EGLE, 2019).

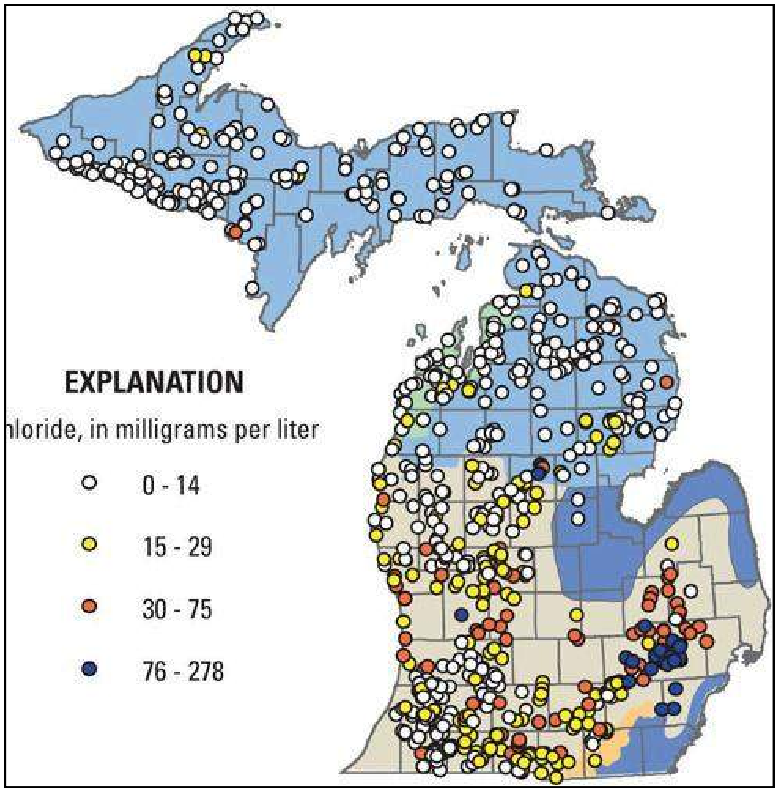

Figure 5. Lake chloride levels (2001–10) in USEPA ecoregions - Fuller and Taricska 2012

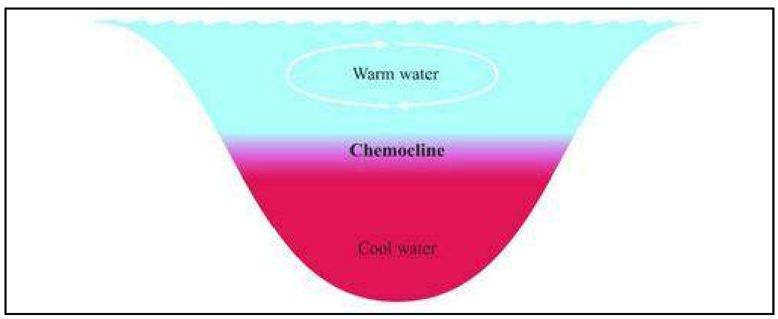

Figure 6. Chloride inputs can result in a chemocline, preventing lake mixing

TOTAL SUSPENDED SOLIDS and TOTAL DISSOLVED SOLIDS

According to EGLE (2020):

Total suspended solids include all particles suspended in water which will not pass through a filter. Most people consider water with a total suspended solids concentration less than 20 mg/L to be clear. Water with total suspended solids levels between 40 and 80 mg/L tends to appear cloudy, while water with concentrations over 150 mg/L usually appears dirty. Total dissolved solids is a measurement of the salts, minerals, and metals dissolved in the water and commonly ranges from 50 to 250 mg/L.

HARDNESS

Hardness in lake water refers to the concentration of calcium and magnesium ions, which can influence the effectiveness of chemical treatments like alum. Acceptable hardness levels in inland lakes for alum treatment typically range from 50 to 200 mg/L (North American Lake Management Society, 2004). High hardness can buffer pH changes, potentially stabilizing water chemistry during alum application. However, extremely high levels may interfere with the flocculation process. Assessing hardness is essential to ensure optimal conditions for successful phosphorus inactivation.

SAMPLING METHODS

Water quality sampling was conducted in the summer and fall of 2024 at the three deep basins within Paw Paw Lake (Figure 9). Temperature and dissolved oxygen were measured at three-foot increments using a YSI Prosolo ODO/T probe. Samples were collected from the surface to just above the lake bottom at 10-foot increments with a Van Dorn bottle (Figure 7) to be analyzed for pH, total alkalinity, hardness, chloride, total suspended solids, soluble reactive phosphorus, and total phosphorus. pH was measured in the field using a Hach Pocket Pro pH meter. Total alkalinity and hardness samples were placed on ice and transported to Progressive Companies for analysis using Standard Methods procedures 2320 B and 2340 C, respectively. Chloride, total suspended solids, soluble reactive phosphorus, and total phosphorus samples were placed on ice and transported to Summit Laboratory* for analysis using Standard Methods procedures 4500-Cl^- B, 2540 D, 4500-P F, and 4500-P E, respectively. In addition to the depth-interval samples at each deep basin, Secchi transparency was measured and composite chlorophyll-*a* samples were collected from the surface to a depth equal to twice the Secchi transparency. Chlorophyll-*a* samples were analyzed by Prein and Newhof Laboratories* using Standard Methods procedure 10200 H.

SAMPLING RESULTS AND DISCUSSION

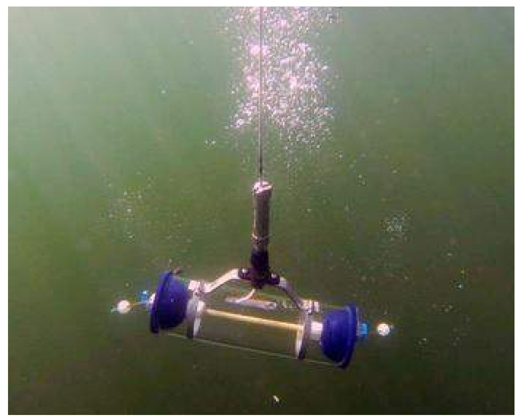
Figure 7. Van Dorn sampler

Water quality sampling results are provided in Tables 4-15. Temperature and dissolved oxygen data are also shown graphically by month in Figures 10-13.

Water quality sampling was conducted during July, August, September, and October. During each sampling event, Paw Paw Lake was thermally stratified; the lake was warm and well-oxygenated at the surface, and was cool with low oxygen near the bottom.

Soluble reactive phosphorus and total phosphorus levels ranged from low to moderate to high in samples taken above the thermocline, increasing with depth as dissolved oxygen levels declined. Phosphorus concentrations were high in the deep, anoxic portions of the lake. The highest phosphorus concentrations during each sampling event were at the bottom at station 3 indicating significant internal loading. The total phosphorus reading at the deepest portion of station 3 in October was 976 µg/L and the SRP was 883 µg/L.

pH and total alkalinity were generally within the moderate range for Upper Midwest lakes.

Chloride concentrations were normal, and well below EGLE's FCV of 150 mg/L.

Total suspended solids levels were generally low, often below the detectable limit of 4.0 mg/L, but ranging up to 18.4 mg/L in the bottom sample at station 3 in October. Total dissolved solids measurements were mostly within the normal range of 50 to 250 mg/L, though some outliers extended beyond that range. The surface sample from station 2 in September was remarkably high at 1,240 mg/L. Samples were not analyzed for total dissolved solids in July.

Hardness samples yielded normal results ranging from 51 to 80 mg/L.

Secchi transparency ranged throughout the study from 6.0 to 12.0 feet across all stations. Over the course of the 4-month study, Secchi transparency averaged 8.9, 8.6, and 8.1 feet at stations 1, 2, and 3, respectively. All three stations exhibited the greatest clarity during the September sampling event.

Chlorophyll-*a* levels were moderate, ranging from 1 to 4 µg/L.

* Summit Laboratory, 900 Godfrey Ave SW, Grand Rapids, MI 49503
* Prein and Newhof Laboratories, 3260 Evergreen Dr NE, Grand Rapids, MI 49525

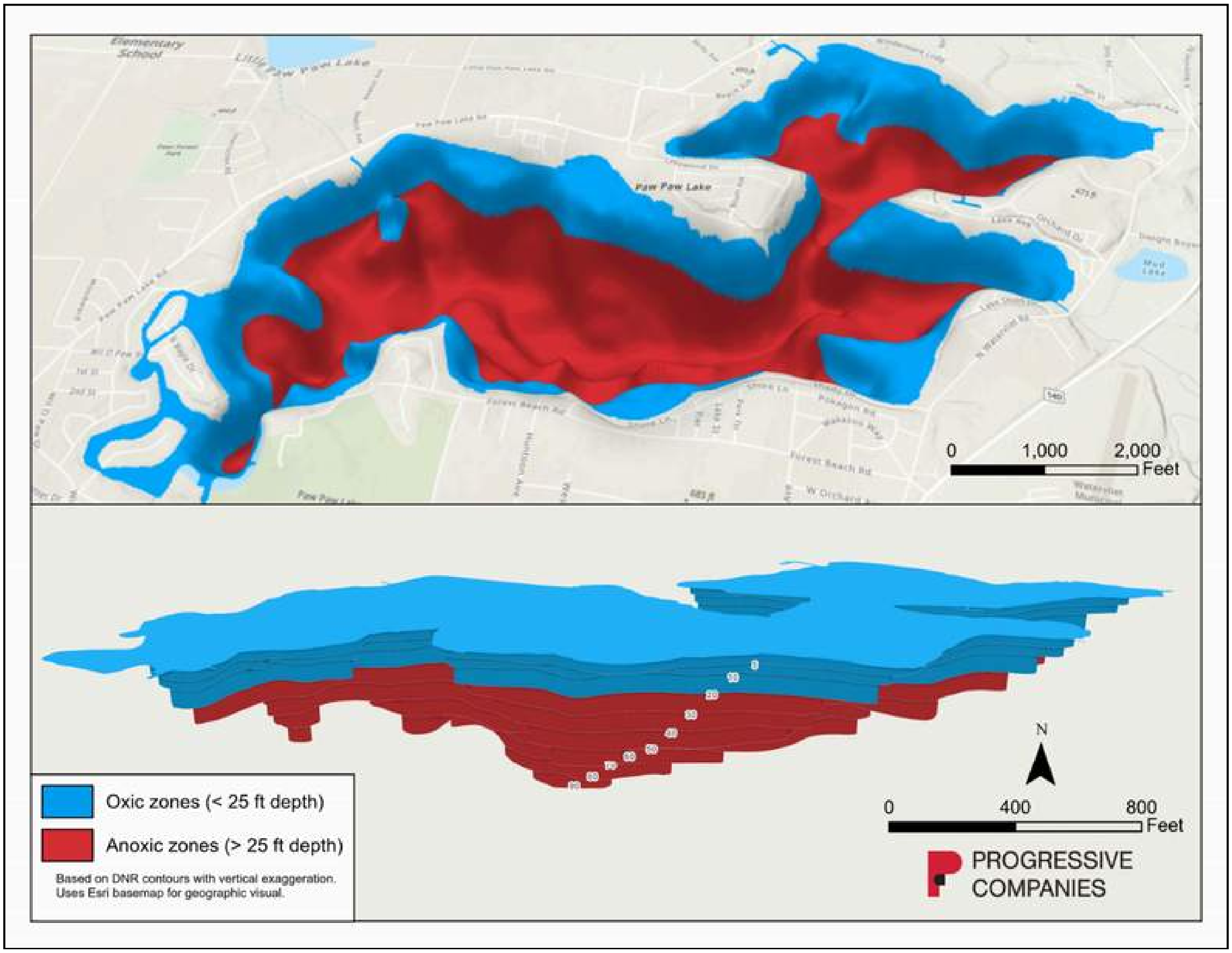

Figure 8. Paw Paw Lake August 2024 Anoxic Zone Map

Dissolved oxygen data collected on August 27, 2024, were used to create a visual representation of oxygenated (blue) and anoxic (red) zones in Paw Paw Lake during summer thermal stratification (Figure 8). At this time, oxygen levels in the water column dropped to approximately 0 mg/L below a depth of 25 feet. The thermocline progressed downward from a depth of approximately 18 feet in July to about 35 feet in October. Due to the density differences between the warm surface water and the cooler bottom layer, vertical mixing was inhibited, resulting in persistent anoxic conditions below the thermocline. These anoxic conditions are maintained until surface water temperatures begin to decline in the fall. The initial stages of this seasonal turnover are evident in the temperature and dissolved oxygen data collected in October (Table 15).

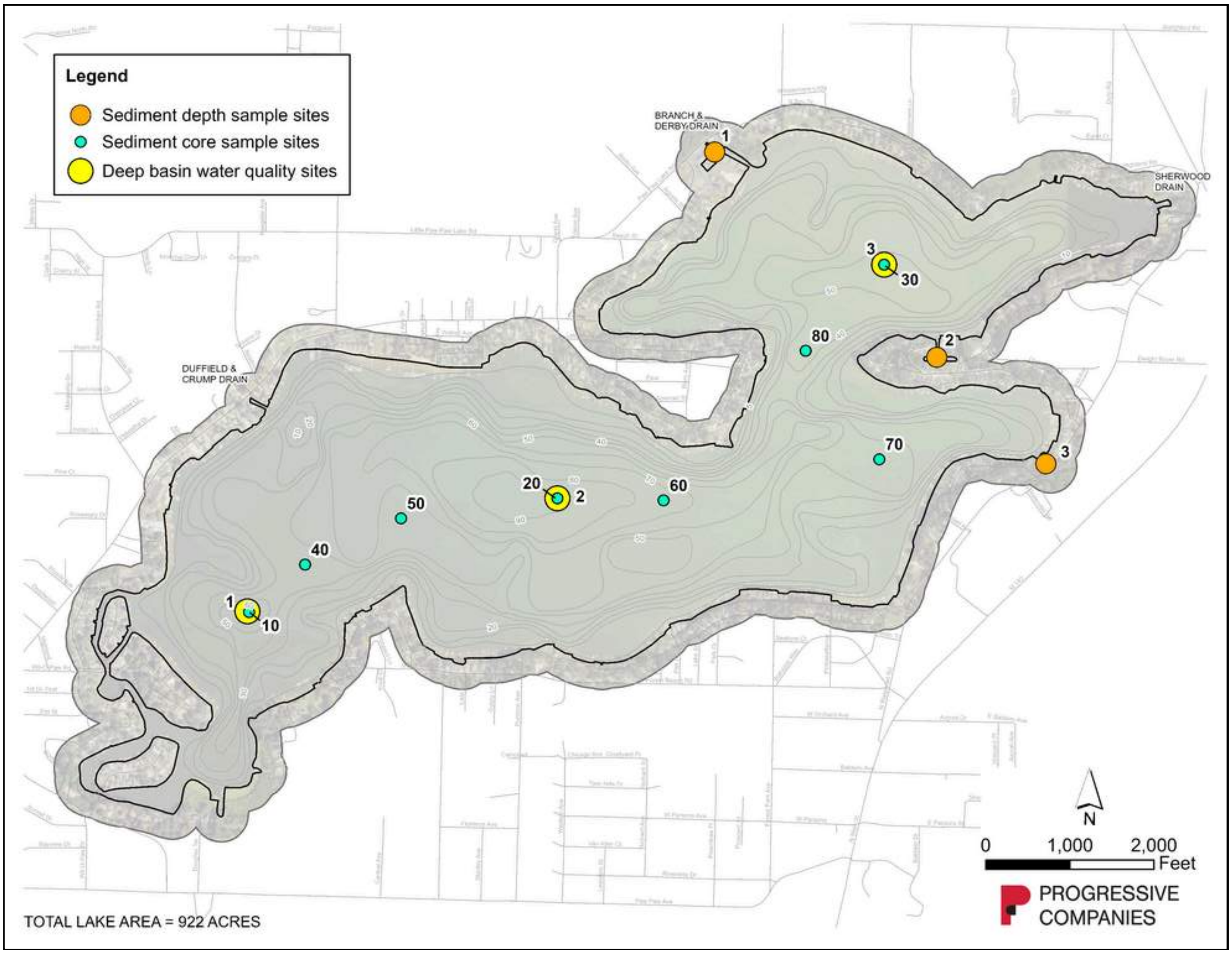

Figure 9. Paw Paw Lake Alum/Dredging Study Sampling Location Map

JULY 2024 WATER QUALITY DATA

TABLE 4 - PAW PAW LAKE 7/11/2024 DEEP BASIN WATER QUALITY DATA

Date	Station	Sample Depth (feet)	Total Phos-phorus (μg/L)*	Soluble Reactive Phos-phorus (μg/L)*	pH (S.U.)*	Total Alkalinity (mg/L CaCO3)*	Chloride (μg/L)*	Total Suspended Solids (mg/L)*	Hardness (mg/L)*
11-Jul-24	1	1	26	<10	8.7	116	9	<4.0	66
11-Jul-24	1	10	19	<10	8.5	116	9	<4.0	66
11-Jul-24	1	20	16	<10	8.0	118	8	<4.0	67
11-Jul-24	1	30	21	<10	7.6	124	8	<4.0	69
11-Jul-24	1	40	34	15	7.5	125	9	5.0	70
11-Jul-24	1	50	91	73	7.7	130	9	4.0	70
11-Jul-24	1	56	117	101	7.6	130	9	4.0	70
11-Jul-24	2	1	20	<10	8.6	112	8	<4.0	64
11-Jul-24	2	10	18	<10	8.4	112	8	<4.0	66
11-Jul-24	2	20	22	<10	8.0	114	9	<4.0	66
11-Jul-24	2	30	14	<10	7.6	115	9	<4.0	67
11-Jul-24	2	40	18	<10	7.6	124	9	<4.0	70
11-Jul-24	2	50	38	26	7.6	125	9	4.0	69
11-Jul-24	2	60	95	71	7.6	127	9	4.0	69
11-Jul-24	2	70	160	128	7.6	127	9	4.8	69
11-Jul-24	2	80	251	197	7.5	130	9	5.2	70
11-Jul-24	2	85	281	265	7.5	131	9	6.4	71
11-Jul-24	3	1	14	<10	8.5	117	8	<4.0	67
11-Jul-24	3	10	22	<10	8.5	118	8	<4.0	67
11-Jul-24	3	20	25	<10	7.7	117	8	<4.0	67
11-Jul-24	3	30	18	<10	7.6	117	9	<4.0	70
11-Jul-24	3	40	123	104	7.5	130	9	9.0	70
11-Jul-24	3	51	360	310	7.4	134	10	6.8	72

TABLE 5 - PAW PAW LAKE 7/11/2024 SURFACE WATER QUALITY DATA

Date	Station	Secchi Transparency (feet)	Chlorophyll-*a* (μg/L)*
11-Jul-24	1	8.0	3
11-Jul-24	2	8.0	3
11-Jul-24	3	7.5	3

* mg/L = milligrams per liter = parts per million
* μg/L = micrograms per liter = parts per billion
* S.U. = standard units
* mg/L CaCO3 = milligrams per liter as calcium carbonate

TABLE 6 - PAW PAW LAKE 7/11/2024 DEEP BASIN TEMPERATURE AND DISSOLVED OXYGEN DATA

Date	Station	Sample Depth (feet)	Temperature (F)	Dissolved Oxygen (mg/L)*
11-Jul-24	1	1	77.5	8.7
11-Jul-24	1	3	76.9	8.9
11-Jul-24	1	6	76.7	8.8
11-Jul-24	1	9	76.5	8.4
11-Jul-24	1	12	76.2	7.3
11-Jul-24	1	15	76.1	7.1
11-Jul-24	1	18	75.2	5.2
11-Jul-24	1	21	73.3	3.0
11-Jul-24	1	24	64.3	0.2
11-Jul-24	1	27	61.2	0.1
11-Jul-24	1	30	57.5	0.0
11-Jul-24	1	33	55.7	0.0
11-Jul-24	1	36	54.3	0.0
11-Jul-24	1	39	53.3	0.0
11-Jul-24	1	42	52.4	0.0
11-Jul-24	1	45	51.9	0.0
11-Jul-24	1	48	51.4	0.0
11-Jul-24	1	51	51.2	0.0
11-Jul-24	1	54	51.0	0.0
11-Jul-24	1	57	50.8	0.0
11-Jul-24	2	1	78.2	9.1
11-Jul-24	2	3	77.6	9.2
11-Jul-24	2	6	76.8	9.2
11-Jul-24	2	9	76.6	9.1
11-Jul-24	2	12	76.5	8.7
11-Jul-24	2	15	76.3	8.3
11-Jul-24	2	18	74.8	4.4
11-Jul-24	2	21	70.4	0.6
11-Jul-24	2	24	66.8	0.2
11-Jul-24	2	27	60.2	0.1
11-Jul-24	2	30	57.4	0.0
11-Jul-24	2	33	55.3	0.0
11-Jul-24	2	36	53.8	0.0
11-Jul-24	2	39	52.9	0.0
11-Jul-24	2	42	52.2	0.0
11-Jul-24	2	45	51.7	0.0
11-Jul-24	2	48	51.0	0.0
11-Jul-24	2	51	50.6	0.0
11-Jul-24	2	54	49.8	0.0
11-Jul-24	2	57	49.5	0.0
11-Jul-24	2	60	49.2	0.0
11-Jul-24	2	63	49.0	0.0
11-Jul-24	2	66	48.6	0.0
11-Jul-24	2	69	48.5	0.0
11-Jul-24	2	72	48.3	0.0
11-Jul-24	2	75	48.2	0.0
11-Jul-24	2	78	48.1	0.0
11-Jul-24	2	81	48.1	0.0
11-Jul-24	2	84	48.0	0.0

* Table 6 continued on following page.

* mg/L = milligrams per liter = parts per million

TABLE 6 CONTINUED

Date	Station	Sample Depth (feet)	Temperature (F)	Dissolved Oxygen (mg/L)*
11-Jul-24	3	1	80.1	9.2
11-Jul-24	3	3	79.0	9.3
11-Jul-24	3	6	77.3	9.3
11-Jul-24	3	9	77.1	9.2
11-Jul-24	3	12	76.7	8.5
11-Jul-24	3	15	76.4	7.9
11-Jul-24	3	18	74.5	4.0
11-Jul-24	3	21	71.7	1.4
11-Jul-24	3	24	67.0	0.2
11-Jul-24	3	27	58.8	0.1
11-Jul-24	3	30	56.6	0.0
11-Jul-24	3	33	54.7	0.0
11-Jul-24	3	36	53.4	0.0
11-Jul-24	3	39	52.1	0.0
11-Jul-24	3	42	51.1	0.0
11-Jul-24	3	45	50.4	0.0
11-Jul-24	3	48	49.9	0.0
11-Jul-24	3	51	49.5	0.0

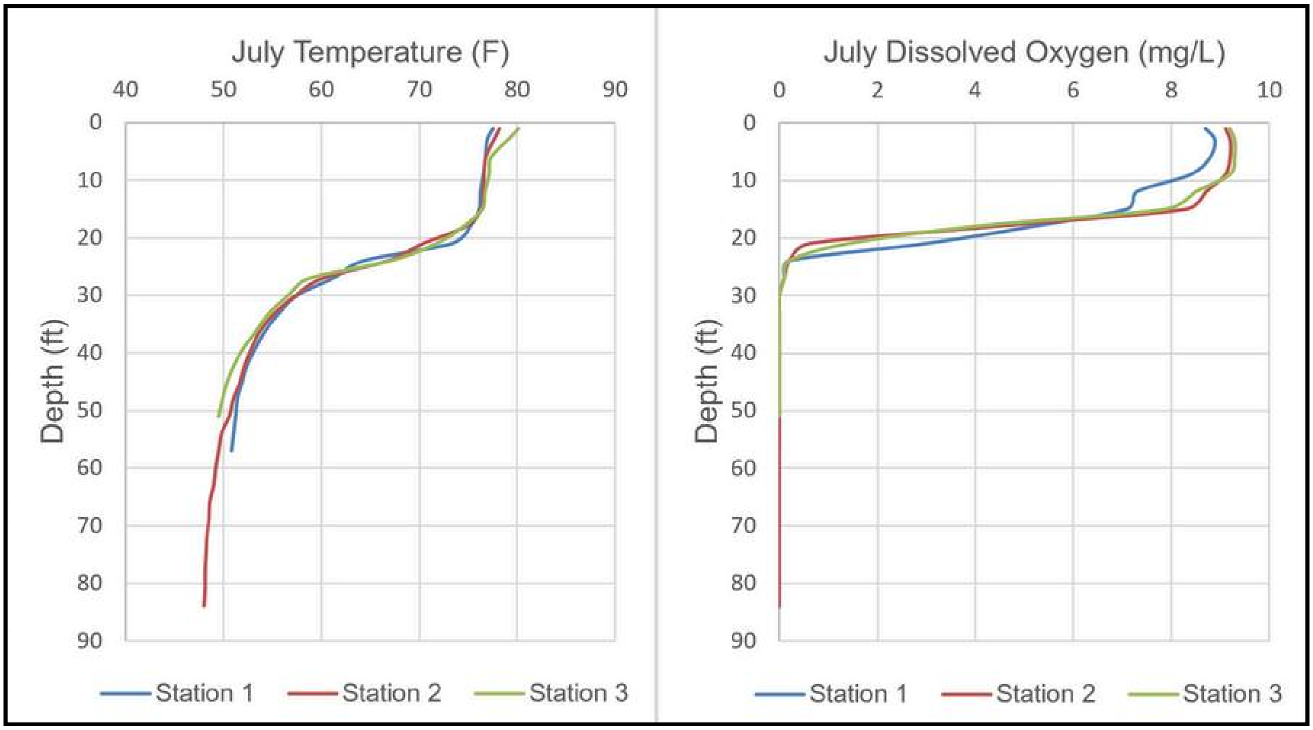

Figure 10. Paw Paw Lake 7/11/2024 Deep Basin Temperature and Dissolved Oxygen

* mg/L = milligrams per liter = parts per million

AUGUST 2024 WATER QUALITY DATA

TABLE 7 - PAW PAW LAKE 8/27/2024 DEEP BASIN WATER QUALITY DATA

Date	Station	Sample Depth (feet)	Total Phosphorus (μg/L)*	Soluble Reactive Phosphorus (μg/L)*	pH (S.U.)*	Total Alkalinity (mg/L CaCO3)*	Chloride (μg/L)*	Total Suspended Solids (mg/L)*	Total Dissolved Solids (mg/L)*	Hardness (mg/L)*
27-Aug-24	1	1	17	<10	8.7	116	11	<4.0	121	60
27-Aug-24	1	10	<10	<10	8.6	115	11	<4.0	133	61
27-Aug-24	1	20	12	<10	7.2	117	11	<4.0	138	64
27-Aug-24	1	30	<10	<10	7.3	130	12	4.8	156	72
27-Aug-24	1	40	51	30	7.2	131	13	<4.0	144	68
27-Aug-24	1	50	128	114	7.1	130	13	4.4	155	68
27-Aug-24	1	54	130	98	7.1	131	12	5.2	187	68
27-Aug-24	2	1	<10	10	8.4	117	10	<4.0	137	51
27-Aug-24	2	10	<10	10	8.4	118	9	<4.0	138	65
27-Aug-24	2	20	<10	10	7.9	120	9	<4.0	145	63
27-Aug-24	2	30	<10	10	7.2	134	10	4.8	278	74
27-Aug-24	2	40	38	24	7.2	127	10	<4.0	144	74
27-Aug-24	2	50	97	82	7.1	130	11	4.4	172	76
27-Aug-24	2	60	163	145	7.1	132	10	6.0	151	79
27-Aug-24	2	70	233	216	7.0	132	11	6.8	176	74
27-Aug-24	2	80	153	143	7.1	128	10	6.0	154	71
27-Aug-24	2	86	322	322	7.0	135	10	7.2	180	73
27-Aug-24	3	1	16	<10	8.2	115	10	4.0	10	66
27-Aug-24	3	10	20	<10	8.1	116	11	<4.0	10	64
27-Aug-24	3	20	14	<10	7.5	117	10	<4.0	10	65
27-Aug-24	3	30	53	<10	7.0	131	17	4.8	26	69
27-Aug-24	3	40	257	244	6.9	141	10	9.6	244	70
27-Aug-24	3	51	510	484	6.8	146	12	14.0	484	72

TABLE 8 - PAW PAW LAKE 8/27/2024 SURFACE WATER QUALITY DATA

Date	Station	Secchi Transparency (feet)	Chlorophyll-*a* (μg/L)*
27-Aug-24	1	7.5	2
27-Aug-24	2	7.5	2
27-Aug-24	3	6.0	4

* mg/L = milligrams per liter = parts per million
* μg/L = micrograms per liter = parts per billion
* S.U. = standard units
* mg/L CaCO3 = milligrams per liter as calcium carbonate

TABLE 9 - PAW PAW LAKE 8/27/2024 DEEP BASIN TEMPERATURE AND DISSOLVED OXYGEN DATA

Date	Station	Sample Depth (feet)	Temperature (F)	Dissolved Oxygen (mg/L)*
27-Aug-24	1	1	79.1	8.1
27-Aug-24	1	3	79.1	8.1
27-Aug-24	1	6	78.9	8.1
27-Aug-24	1	9	78.6	8.0
27-Aug-24	1	12	77.2	7.6
27-Aug-24	1	15	74.9	5.5
27-Aug-24	1	18	74.4	5.2
27-Aug-24	1	21	72.5	2.6
27-Aug-24	1	24	68.4	0.0
27-Aug-24	1	27	67.3	0.0
27-Aug-24	1	30	59.6	0.0
27-Aug-24	1	33	58.8	0.0
27-Aug-24	1	36	56.9	0.0
27-Aug-24	1	39	55.9	0.0
27-Aug-24	1	42	54.8	0.0
27-Aug-24	1	45	53.2	0.0
27-Aug-24	1	48	52.6	0.0
27-Aug-24	1	51	51.6	0.0
27-Aug-24	1	54	51.8	0.0
27-Aug-24	2	1	79.4	8.1
27-Aug-24	2	3	79.2	8.1
27-Aug-24	2	6	78.2	7.4
27-Aug-24	2	9	76.2	6.6
27-Aug-24	2	12	76.0	6.6
27-Aug-24	2	15	75.0	6.1
27-Aug-24	2	18	74.3	5.2
27-Aug-24	2	21	73.6	3.9
27-Aug-24	2	24	70.4	0.0
27-Aug-24	2	27	65.5	0.0
27-Aug-24	2	30	58.8	0.0
27-Aug-24	2	33	57.4	0.0
27-Aug-24	2	36	53.4	0.0
27-Aug-24	2	39	52.1	0.0
27-Aug-24	2	42	51.6	0.0
27-Aug-24	2	45	51.2	0.0
27-Aug-24	2	48	50.5	0.0
27-Aug-24	2	51	49.7	0.0
27-Aug-24	2	54	49.6	0.0
27-Aug-24	2	57	49.2	0.0
27-Aug-24	2	60	49.0	0.0
27-Aug-24	2	63	48.7	0.0
27-Aug-24	2	66	48.6	0.0
27-Aug-24	2	69	48.5	0.0
27-Aug-24	2	72	48.4	0.0
27-Aug-24	2	75	48.3	0.0
27-Aug-24	2	78	48.3	0.0
27-Aug-24	2	81	48.3	0.0
27-Aug-24	2	84	48.3	0.0
27-Aug-24	2	86	48.3	0.0

* Table 9 continued on following page.

* mg/L = milligrams per liter = parts per million

TABLE 9 CONTINUED

Date	Station	Sample Depth (feet)	Temperature (F)	Dissolved Oxygen (mg/L)*
27-Aug-24	3	1	79.9	8.5
27-Aug-24	3	3	79.8	8.5
27-Aug-24	3	6	79.7	8.4
27-Aug-24	3	9	79.4	8.2
27-Aug-24	3	12	75.7	6.1
27-Aug-24	3	15	74.8	5.2
27-Aug-24	3	18	74.7	4.6
27-Aug-24	3	21	73.3	3.1
27-Aug-24	3	24	69.3	0.1
27-Aug-24	3	27	62.1	0.1
27-Aug-24	3	30	57.5	0.0
27-Aug-24	3	33	55.6	0.0
27-Aug-24	3	36	52.9	0.0
27-Aug-24	3	39	52.4	0.0
27-Aug-24	3	42	51.5	0.1
27-Aug-24	3	45	50.6	0.1
27-Aug-24	3	48	50.3	0.1
27-Aug-24	3	51	50.4	0.1

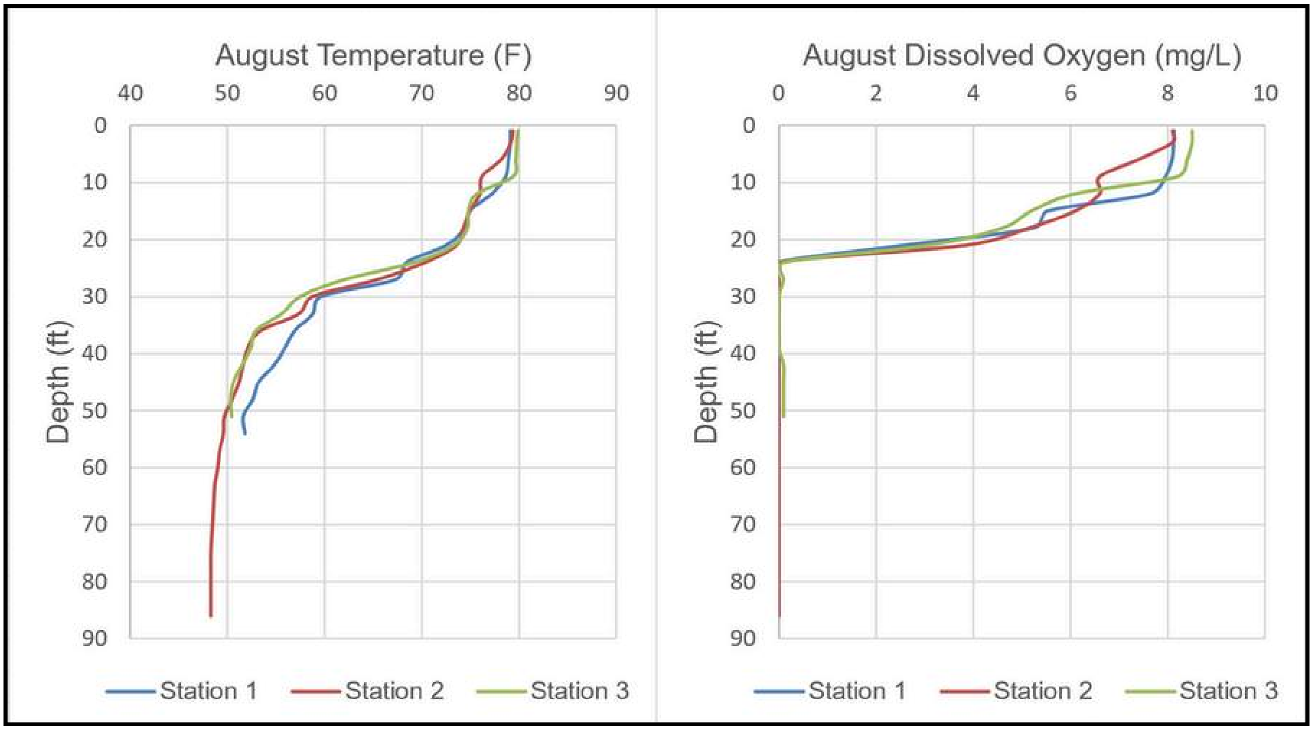

Figure 11. Paw Paw Lake 8/27/2024 Deep Basin Temperature and Dissolved Oxygen

* mg/L = milligrams per liter = parts per million

SEPTEMBER 2024 WATER QUALITY DATA

TABLE 10 - PAW PAW LAKE 9/26/2024 DEEP BASIN WATER QUALITY DATA

Date	Station	Sample Depth (feet)	Total Phosphorus (µg/L)*	Soluble Reactive Phosphorus (µg/L)*	pH (S.U.)*	Total Alkalinity (mg/L CaCO3)*	Chloride (µg/L)*	Total Suspended Solids (mg/L)*	Total Dissolved Solids (mg/L)*	Hardness (mg/L)*
26-Sep-24	1	1	<10	<10	8.3	116	10	<4.0	159	74
26-Sep-24	1	10	<10	<10	8.2	117	10	<4.0	144	74
26-Sep-24	1	20	22	<10	7.8	117	11	<4.0	148	68
26-Sep-24	1	30	25	<10	7.5	127	12	5.2	178	70
26-Sep-24	1	40	72	65	7.4	131	11	4.4	185	72
26-Sep-24	1	50	165	116	7.3	135	11	<4.0	184	71
26-Sep-24	1	55	159	157	7.3	135	12	4.8	188	72
26-Sep-24	2	1	24	<10	7.8	16	17	4.0	1240	69
26-Sep-24	2	10	10	<10	7.8	118	10	<4.0	165	68
26-Sep-24	2	20	19	<10	7.8	118	11	<4.0	172	68
26-Sep-24	2	30	<10	<10	7.1	124	10	4.4	167	69
26-Sep-24	2	40	70	55	7.0	127	13	4.0	174	71
26-Sep-24	2	50	126	101	7.0	128	12	4.8	171	72
26-Sep-24	2	60	217	174	6.9	130	10	4.4	191	72
26-Sep-24	2	70	304	255	6.9	131	11	<4.0	188	72
26-Sep-24	2	80	330	280	6.9	135	15	<4.0	185	73
26-Sep-24	2	86	324	288	6.9	137	14	<4.0	196	73
26-Sep-24	3	1	<10	<10	7.9	117	10	<4.0	170	65
26-Sep-24	3	10	<10	<10	7.8	118	11	<4.0	173	67
26-Sep-24	3	20	24	<10	7.7	118	11	<4.0	168	67
26-Sep-24	3	30	32	20	7.1	126	13	5.6	179	70
26-Sep-24	3	40	297	273	7.0	139	10	6.8	187	73
26-Sep-24	3	48	682	677	6.9	145	10	13.0	180	73

TABLE 11 - PAW PAW LAKE 9/26/2024 SURFACE WATER QUALITY DATA

Date	Station	Secchi Transparency (feet)	Chlorophyll-*a* (µg/L)*
26-Sep-24	1	12.0	1
26-Sep-24	2	12.0	2
26-Sep-24	3	10.0	1

* mg/L = milligrams per liter = parts per million
* µg/L = micrograms per liter = parts per billion
* S.U. = standard units
* mg/L CaCO3 = milligrams per liter as calcium carbonate

TABLE 12 - PAW PAW LAKE 9/26/2024 DEEP BASIN TEMPERATURE AND DISSOLVED OXYGEN DATA

Date	Station	Sample Depth (feet)	Temperature (F)	Dissolved Oxygen (mg/L)*
26-Sep-24	1	1	72.1	6.5
26-Sep-24	1	3	72.1	6.5
26-Sep-24	1	6	71.9	6.4
26-Sep-24	1	9	71.8	6.3
26-Sep-24	1	12	71.8	6.2
26-Sep-24	1	15	71.7	5.8
26-Sep-24	1	18	71.6	5.0
26-Sep-24	1	21	71.2	3.1
26-Sep-24	1	24	70.9	2.4
26-Sep-24	1	27	65.6	0.0
26-Sep-24	1	30	60.2	0.0
26-Sep-24	1	33	57.9	0.0
26-Sep-24	1	36	55.5	0.0
26-Sep-24	1	39	54.4	0.0
26-Sep-24	1	42	52.1	0.0
26-Sep-24	1	45	51.8	0.0
26-Sep-24	1	48	51.6	0.0
26-Sep-24	1	51	51.4	0.0
26-Sep-24	1	54	51.4	0.0
26-Sep-24	2	1	72.5	6.7
26-Sep-24	2	3	72.4	6.7
26-Sep-24	2	6	72.1	6.6
26-Sep-24	2	9	72.0	6.4
26-Sep-24	2	12	71.9	6.4
26-Sep-24	2	15	71.9	6.4
26-Sep-24	2	18	71.8	6.4
26-Sep-24	2	21	71.5	6.3
26-Sep-24	2	24	70.3	2.1
26-Sep-24	2	27	67.7	0.0
26-Sep-24	2	30	60.4	0.0
26-Sep-24	2	33	57.4	0.0
26-Sep-24	2	36	54.7	0.0
26-Sep-24	2	39	53.4	0.0
26-Sep-24	2	42	52.6	0.0
26-Sep-24	2	45	51.6	0.0
26-Sep-24	2	48	51.0	0.0
26-Sep-24	2	51	50.2	0.0
26-Sep-24	2	54	49.7	0.0
26-Sep-24	2	57	49.4	0.0
26-Sep-24	2	60	49.1	0.0
26-Sep-24	2	63	48.9	0.0
26-Sep-24	2	66	48.8	0.0
26-Sep-24	2	69	48.7	0.0
26-Sep-24	2	72	48.6	0.0
26-Sep-24	2	75	48.6	0.0
26-Sep-24	2	78	48.6	0.0
26-Sep-24	2	81	48.6	0.0
26-Sep-24	2	84	48.6	0.0
26-Sep-24	2	86	48.5	0.0

* Table 12 continued on following page.

* mg/L = milligrams per liter = parts per million

TABLE 12 CONTINUED

Date	Station	Sample Depth (feet)	Temperature (F)	Dissolved Oxygen (mg/L)*
26-Sep-24	3	1	72.5	6.6
26-Sep-24	3	3	72.4	6.5
26-Sep-24	3	6	72.4	6.5
26-Sep-24	3	9	71.9	6.2
26-Sep-24	3	12	71.8	6.1
26-Sep-24	3	15	71.8	6.1
26-Sep-24	3	18	71.7	5.5
26-Sep-24	3	21	71.2	3.1
26-Sep-24	3	24	70.0	0.8
26-Sep-24	3	27	65.5	0.0
26-Sep-24	3	30	60.2	0.0
26-Sep-24	3	33	58.4	0.0
26-Sep-24	3	36	54.0	0.0
26-Sep-24	3	39	51.3	0.0
26-Sep-24	3	42	51.0	0.0
26-Sep-24	3	45	50.8	0.0
26-Sep-24	3	48	50.7	0.0

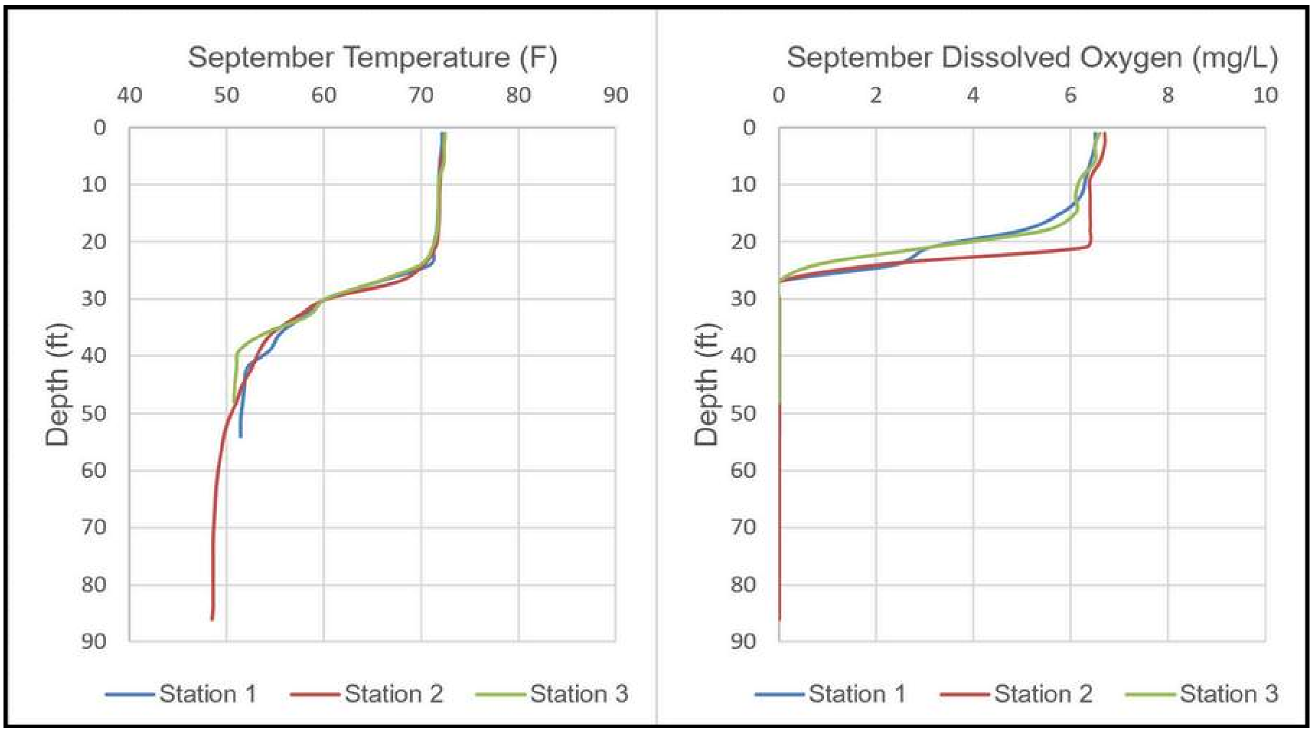

Figure 12. Paw Paw Lake 9/26/2024 Deep Basin Temperature and Dissolved Oxygen

* mg/L = milligrams per liter = parts per million

OCTOBER 2024 WATER QUALITY DATA

TABLE 13 - PAW PAW LAKE 10/22/2024 DEEP BASIN WATER QUALITY DATA

Date	Station	Sample Depth (feet)	Total Phosphorus (µg/L)*	Soluble Reactive Phosphorus (µg/L)*	pH (S.U.)*	Total Alkalinity (mg/L CaCO3)*	Chloride (µg/L)*	Total Suspended Solids (mg/L)*	Total Dissolved Solids (mg/L)*	Hardness (mg/L)*
22-Oct-24	1	1	21	<10	7.9	121	11	<4.0	180	65
22-Oct-24	1	10	<10	<10	8.0	121	10	<4.0	169	65
22-Oct-24	1	20	<10	<10	7.9	121	10	4.0	174	65
22-Oct-24	1	30	15	<10	7.8	123	15	<4.0	172	65
22-Oct-24	1	40	56	15	7.4	124	12	5.2	173	72
22-Oct-24	1	50	178	135	7.2	135	9	<4.0	189	66
22-Oct-24	1	55	252	212	7.2	141	11	5.2	196	70
22-Oct-24	2	1	10	<10	8.0	122	17	<4.0	170	66
22-Oct-24	2	10	13	<10	8.0	121	8	<4.0	166	67
22-Oct-24	2	20	<10	<10	7.9	118	11	<4.0	162	65
22-Oct-24	2	30	<10	<10	7.8	122	10	<4.0	162	65
22-Oct-24	2	40	70	<10	7.3	127	10	<4.0	173	68
22-Oct-24	2	50	157	125	7.1	139	9	<4.0	171	72
22-Oct-24	2	60	275	241	7.1	141	10	<4.0	176	73
22-Oct-24	2	70	325	266	7.1	141	11	<4.0	186	73
22-Oct-24	2	80	398	361	7.0	135	10	<4.0	183	72
22-Oct-24	2	87	389	335	7.0	137	10	<4.0	182	73
22-Oct-24	3	1	<10	<10	7.9	117	9	<4.0	166	76
22-Oct-24	3	10	<10	<10	7.9	122	9	<4.0	161	65
22-Oct-24	3	20	<10	<10	7.7	120	10	<4.0	162	65
22-Oct-24	3	30	<10	<10	7.6	120	9	5.0	168	69
22-Oct-24	3	40	169	114	7.1	148	14	6.4	184	80
22-Oct-24	3	51	976	883	6.9	153	13	18.4	199	75

TABLE 14 - PAW PAW LAKE 10/22/2024 SURFACE WATER QUALITY DATA

Date	Station	Secchi Transparency (feet)	Chlorophyll-*a* (µg/L)*
22-Oct-24	1	8.0	2
22-Oct-24	2	7.0	3
22-Oct-24	3	9.0	2

* mg/L = milligrams per liter = parts per million
* µg/L = micrograms per liter = parts per billion
* S.U. = standard units
* mg/L CaCO3 = milligrams per liter as calcium carbonate

TABLE 15 - PAW PAW LAKE 10/22/2024 DEEP BASIN TEMPERATURE AND DISSOLVED OXYGEN DATA

Date	Station	Sample Depth (feet)	Temperature (F)	Dissolved Oxygen (mg/L)*
22-Oct-24	1	1	60.7	7.3
22-Oct-24	1	3	60.6	7.3
22-Oct-24	1	6	60.6	7.2
22-Oct-24	1	9	60.5	7.2
22-Oct-24	1	12	60.5	7.1
22-Oct-24	1	15	60.4	7.0
22-Oct-24	1	18	60.4	6.9
22-Oct-24	1	21	60.3	6.9
22-Oct-24	1	24	60.3	6.8
22-Oct-24	1	27	60.2	6.8
22-Oct-24	1	30	60.1	6.5
22-Oct-24	1	33	59.9	6.3
22-Oct-24	1	36	59.1	5.2
22-Oct-24	1	39	55.6	0.1
22-Oct-24	1	42	52.6	0.1
22-Oct-24	1	45	51.8	0.2
22-Oct-24	1	48	51.7	0.3
22-Oct-24	1	51	51.5	0.3
22-Oct-24	1	54	51.3	0.4
22-Oct-24	2	1	61.1	7.6
22-Oct-24	2	3	60.9	7.5
22-Oct-24	2	6	60.9	7.5
22-Oct-24	2	9	60.9	7.4
22-Oct-24	2	12	60.9	7.4
22-Oct-24	2	15	60.8	7.4
22-Oct-24	2	18	60.8	7.3
22-Oct-24	2	21	60.8	7.2
22-Oct-24	2	24	60.7	7.2
22-Oct-24	2	27	60.6	6.8
22-Oct-24	2	30	60.2	6.4
22-Oct-24	2	33	59.6	5.4
22-Oct-24	2	36	58.8	3.4
22-Oct-24	2	39	57.1	0.0
22-Oct-24	2	42	54.1	0.0
22-Oct-24	2	45	51.8	0.0
22-Oct-24	2	48	50.8	0.0
22-Oct-24	2	51	49.9	0.0
22-Oct-24	2	54	49.7	0.0
22-Oct-24	2	57	49.4	0.0
22-Oct-24	2	60	49.2	0.0
22-Oct-24	2	63	49.2	0.0
22-Oct-24	2	66	49.0	0.0
22-Oct-24	2	69	48.7	0.0
22-Oct-24	2	72	48.7	0.0
22-Oct-24	2	75	48.5	0.0
22-Oct-24	2	78	48.5	0.0
22-Oct-24	2	81	48.5	0.0
22-Oct-24	2	84	48.5	0.0
22-Oct-24	2	87	48.6	0.1

* Table 15 continued on following page.

* mg/L = milligrams per liter = parts per million

TABLE 15 CONTINUED

Date	Station	Sample Depth (feet)	Temperature (F)	Dissolved Oxygen (mg/L)*
22-Oct-24	3	1	61.5	7.9
22-Oct-24	3	3	61.5	7.9
22-Oct-24	3	6	61.4	7.8
22-Oct-24	3	9	61.4	7.7
22-Oct-24	3	12	61.3	7.6
22-Oct-24	3	15	61.3	7.5
22-Oct-24	3	18	60.9	7.0
22-Oct-24	3	21	60.6	6.2
22-Oct-24	3	24	60.5	5.9
22-Oct-24	3	27	60.3	5.6
22-Oct-24	3	30	60.1	5.2
22-Oct-24	3	33	59.9	4.5
22-Oct-24	3	36	58.0	0.0
22-Oct-24	3	39	54.2	0.0
22-Oct-24	3	42	52.6	0.0
22-Oct-24	3	45	51.1	0.0
22-Oct-24	3	48	50.6	0.0
22-Oct-24	3	51	50.4	0.0

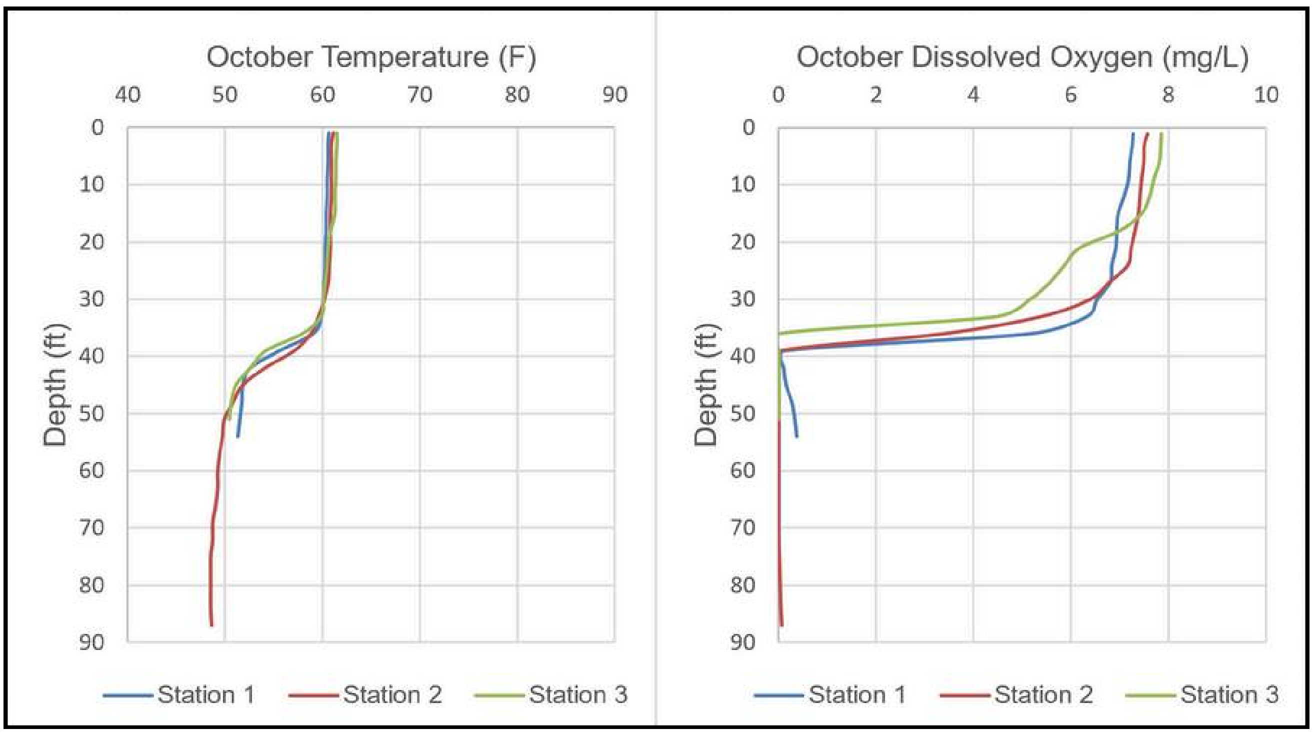

Figure 13. Paw Paw Lake 10/22/2024 Deep Basin Temperature and Dissolved Oxygen

* mg/L = milligrams per liter = parts per million

SEDIMENT ANALYSIS

On October 21, 2024 staff from Barr Engineering and Progressive Companies collected sediment cores from a total of 8 sites in a longitudinal orientation from southwest to northeast across the deepest portions of Paw Paw Lake using the Aquatic Research Instruments Hope ID gravity coring device. Samples were placed on ice and delivered intact to Barr's laboratory in Minneapolis, MN. Each core was then sectioned vertically and analyzed for mobile phosphorus fractions, inactive aluminum-bound phosphorus fractions, total iron, and aluminum.

Additional cores at stations 10, 20, and 30 (the three deep basins) were collected and used to evaluate sediment phosphorus release rates while incubated under anoxic conditions. Each were analyzed using three different methods and results were compared. Comparison of data suggests that the northeast basin contributes the highest relative redox phosphorus followed by the central basin and to a much lesser degree, the southwest basin. It is recommended that phosphorus mitigation efforts should focus on the northeast basin and the central basin at depths below 40 feet.

Further information on the sediment coring and analysis portion of this study can be found in the Barr Engineering report (Appendix A).

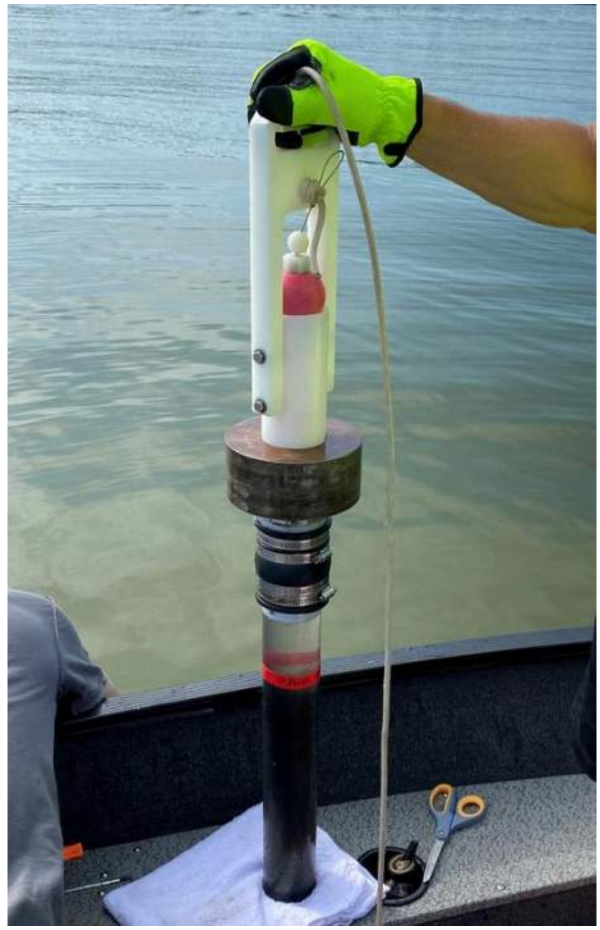

Figure 14. Sediment core sampler

ALUM

Alum (aluminum sulfate) is a chemical that has been used successfully in many lakes to reduce internal phosphorus loading and improve water quality. Once applied, alum binds with phosphorus in the water column and settles to the bottom as an aluminum hydroxide floc. The floc inhibits the release of phosphorus from lake sediments. Properties of aluminum hydroxide of greatest interest to lake managers are its apparent low or zero toxicity to lake biota (organisms), its inherent ability to adsorb large amounts of particulate and soluble phosphorus, and its ability to bind phosphorus even in anoxic (oxygen free) conditions. In lakes with high rates of internal phosphorus loading, alum can be an effective tool to reduce phosphorus levels in the water column, improve water clarity, and reduce the frequency and duration of algae blooms. Alum has been effectively used for coagulation in water treatment for over 200 years and is probably the most commonly used drinking water treatment in the world (Ødegaard et al., 1990).

Alum is typically applied to a lake with a specialized barge (Figure 15) over the portions of the lake affected by internal phosphorus loading. Alum is applied evenly over these areas to achieve a specified target dose based upon sediment testing and incubated sediment laboratory trials. The application of alum can result in a short term lowering of pH. However, a buffering additive, such as sodium aluminate, is often added to maintain a safe pH range during and after application. When properly dosed and applied, there are no swimming, fishing, or irrigation restrictions during an alum treatment.

Because the expected release of soluble reactive phosphorus below the thermocline did not occur until approximately 40 feet deep during all of the sampling events at all three sampling sites, phosphorus mitigation should be prioritized at depths of 40 feet and below, and not the entirety of the hypolimnion (zone below the thermocline). Concentrating resources in these areas would result in substantial savings. An estimate of typical alum treatment cost scenarios is provided in the Barr Engineering report (Appendix A).

Figure 15. Alum treatment

HYPOLIMNETIC OXYGENATION

Hypolimnetic oxygenation systems are designed to increase dissolved oxygen in the hypolimnion (zone below the thermocline) of a lake while not disturbing or breaking down natural stratification cycles. There is significant evidence to support both oxygenation and aeration systems as effective strategies to increase hypolimnion dissolved oxygen levels and reduce internal loading. However, they work best in very deep, stratified lakes and they must be evenly distributed across a lake and properly sized. Using these systems in a shallow lake or shallow portions of a lake will not have the desired effect, because the mechanisms require a deep hypolimnion to not disturb thermal stratification and may even increase nutrient loading by circulating nutrients into the epilimnion (upper layer) where they are readily available for algal use (Interstate Regulatory Technology Council, n.d.).

Hypolimnetic oxygenation in deep lakes can be an effective management strategy with numerous potential water quality benefits including: maintenance of an oxygenated source of cool water to meet consumer and environmental needs, decreases in internal nutrient loading, inhibition of sediment release of problematic reduced compounds, and maintenance of summertime habitat for cold-water fish, zooplankton and zoobenthos (Wiedeman, 1999). The use of pure oxygen pumped into the hypolimnion, while more expensive, compares favorably to aeration. "Compared to hypolimnetic aeration, oxygenation results in higher hypolimnetic dissolved oxygen levels, lower levels of induced oxygen demand, and maintenance of more stable thermal stratification" (Wiedeman, 1999).

A 2019 issue of *Lake and Reservoir Management* is dedicated to oxygenation. Its preface "advances in hypolimnetic oxygenation" states that pure oxygenation seems to be the most efficient and cost-effective method of oxygenate a hypolimnion with a thickness of 6 meters (20 feet or more), but any thinner and it may cause disruption of thermal destratification or early turnover. Small-scale pure oxygenation systems are now available on the market and may be feasible for use on recreational lakes. In the future, advances in oxygen generators will bring down costs by limiting the need to truck around oxygen tanks. Supersaturation chambers are an even newer technology that removes water, saturates it, and then redeploys it at a targeted depth. This technology is promising but its potential is not yet fully tapped. Costs for hypolimnetic aeration are generally in the $1,500 - $3,000 per acre for capital costs and $50 - $100 per acre per year for operation and maintenance costs (Wiedeman & Steinman, 2022).

DREDGING

As part of this study, the necessity and feasibility of dredging specific channels on Paw Paw Lake were evaluated, including the Lake Stella connector, the Branch/Derby inlet channel, and the channel near Elm Drive (Figure 18). To assess current navigability and the potential need for sediment removal, water and sediment depths were measured throughout these channels using range poles (Table 16).

Dredging is commonly used to maintain water depth, improve navigation, and manage sediment buildup. The two primary methods are hydraulic and mechanical dredging. Hydraulic dredging uses pumps to move soft sediment and water through pipes to a containment area or dewatering bag (Figure 16), making it suitable for large areas with fine material. Mechanical dredging, using backhoes or clamshell buckets (Figure 17), is better for smaller areas or heavier materials like gravel.

Figure 16. Dewatering geotextile bag for hydraulic dredging

Prior to dredging, sediment sampling is essential to determine material type and test for contaminants such as heavy metals or organic pollutants. These results guide both the choice of dredging method and how the material must be handled or disposed of, which can significantly affect project cost.

However, dredging can also have environmental consequences, including habitat disruption, increased turbidity, and nutrient release. Proper planning and mitigation measures—like using silt curtains—are necessary to minimize these impacts. Mechanical dredging, in particular, can cause shoreline erosion if not carefully managed.

Figure 17. Mechanical dredging with an excavator

In Michigan, dredging projects require a permit from the Department of Environment, Great Lakes, and Energy (EGLE), which involves submitting detailed plans, test results, and possibly public notices. The permitting process can be lengthy, and costs vary depending on project scale and site conditions.

Based on sediment depth data collected in this study, the Branch/Derby and Elm Drive channels do not currently exhibit sediment accumulation at levels significant enough to warrant dredging. Water depths remain sufficient for navigation, and dredging in these areas would likely yield limited benefit when weighed against the associated costs and potential ecological disruption.

In contrast, the channel leading to Lake Stella shows signs of shallowing, particularly in the first half of the channel when entering from Paw Paw Lake. Water depths in this section range from approximately 1.5 to 2.0 feet, with soft sediment depths between 1.0 and 6.0 feet.

Dredging of the Lake Stella channel between points 1 and 6 (Figure 18) would likely be beneficial to achieve a consistent navigable depth of 4.0 feet. Based on linear interpolation between sample sites, an average channel width of 30.0 feet, and a dredging length of 579.0 feet, it is estimated that approximately 1,222 cubic yards of soft sediment would need to be removed from this segment. Several factors might influence the cost of such a project, including permitting, sediment testing, engineering and environmental consulting, dredging methods and operations, material disposal, and monitoring/compliance requirements. Cost estimation can be further complicated by the presence of contaminated sediment, which may significantly increase expenses related to permitting, testing, disposal, and long-term monitoring. The estimated cost to dredge 1,222 cubic yards from the Lake Stella channel in 2026 ranges from approximately $105,000 to $250,000, depending on sediment quality and disposal requirements. If the sediment is clean and can be disposed of locally, costs may stay between $105,000 and $125,000. However, if the sediment is contaminated and requires extensive testing, special handling, and regulated landfill disposal, the total cost could rise to $180,000–$250,000.

Should dredging in this area be proposed, a more extensive study would be required to asses goals, EGLE permit requirements, disposal options, environmental impacts, and costs.

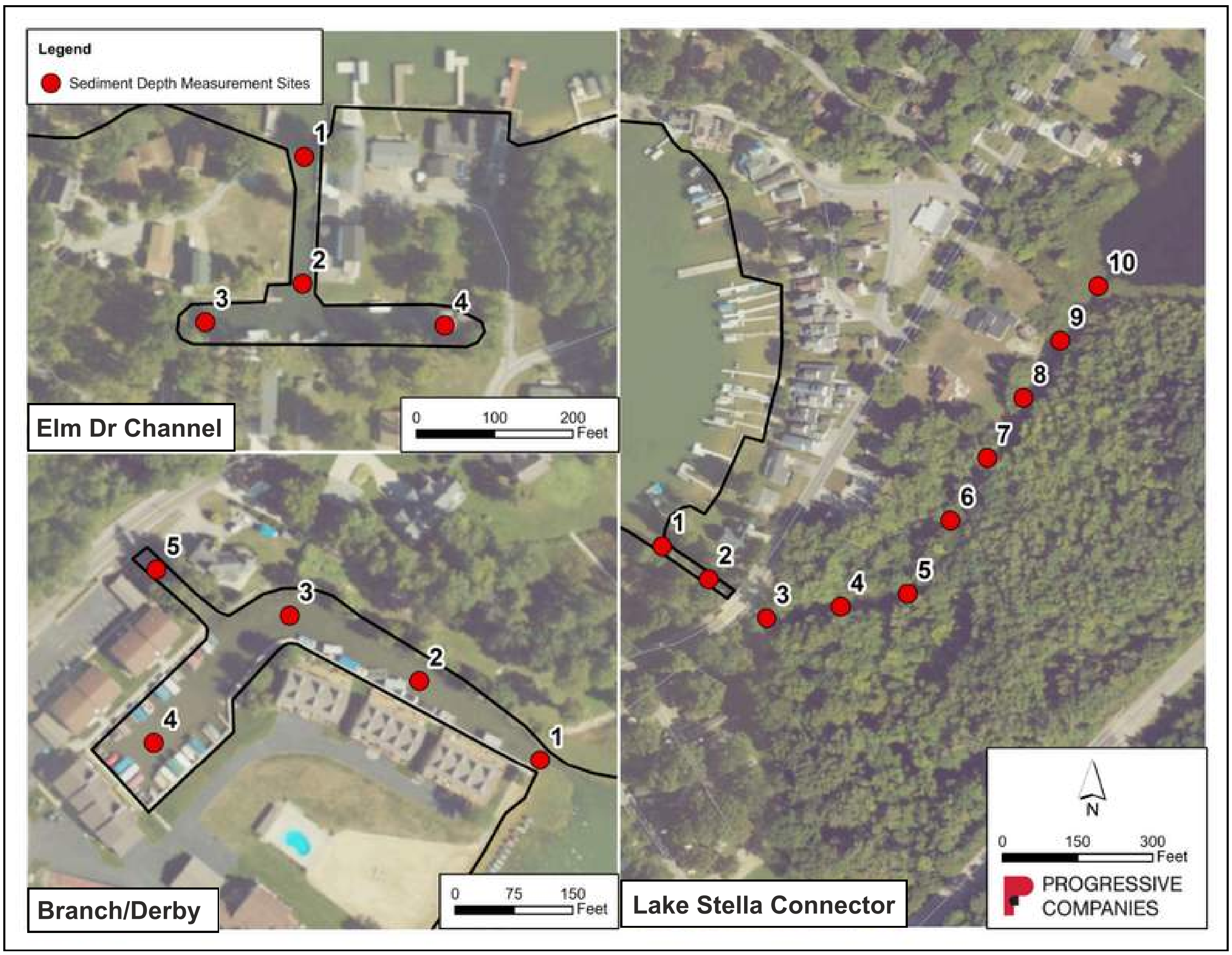

Figure 18. Paw Paw Lake Tributary/Channel Sediment Depth Measurement Sites

TABLE 16 - PAW PAW LAKE 4/14/2025 TRIBUTARY/CHANNEL SEDIMENT DEPTH MEASUREMENTS

Site	Channel	Sediment Depth (feet)	Water Depth (feet)
1	Stella Connector	1.0	2.0
2	Stella Connector	4.5	1.5
3	Stella Connector	5.5	2.5
4	Stella Connector	4.0	1.5
5	Stella Connector	6.0	2.0
6	Stella Connector	3.0	4.0
7	Stella Connector	2.0	4.0
8	Stella Connector	3.0	4.0
9	Stella Connector	3.5	3.5
10	Stella Connector	9.0	4.0
1	Branch/Derby	3.5	2.5
2	Branch/Derby	4.0	4.0
3	Branch/Derby	3.0	4.5
4	Branch/Derby	5.5	5.0
5	Branch/Derby	1.0	3.0
1	Elm Dr Channel	3.0	4.0
2	Elm Dr Channel	3.5	4.0
3	Elm Dr Channel	9.5	4.0
4	Elm Dr Channel	3.0	4.0

RECOMMENDATIONS

Based upon the results of this study, the following recommendations are being suggested for reducing the concentration and availability of soluble reactive phosphorus in the hypolimnion (deep portions) of Paw Paw Lake. By reducing the available phosphorus to vertical migrating algal species such as *Microcystis aeruginosa*, the frequency and duration of harmful algal blooms (HABs) on Paw Paw Lake likely will be greatly reduced and overall clarity will increase. It should be noted that mitigating available phosphorus is a two-pronged problem. To effectively reduce phosphorus levels in Paw Paw Lake, efforts must be applied to both external sources (from its 9,200-acre watershed) and internal sources (legacy phosphorus being released from the deep sediments). Watershed efforts are ongoing and several projects have been or are currently being undertaken to reduce nutrient loading from Paw Paw Lake's watershed. These important projects should be continued and expanded for the betterment of the lake's ecology and water quality. This report addresses only proposed internal phosphorus mitigation options.

To address internal phosphorus loading, we recommend a sequential approach in two phases over several years beginning with a focused alum treatment in the lake's most nutrient enriched basin (Station 3, Figure 9) in the northeast portion of the lake. This phase of the plan would only take place if approved at public hearings and is estimated to cost approximately $587,000. The estimated duration of effectiveness for this approach in the northeast basin would be between 10-20 years and the duration of effectiveness would be highly dependent upon ongoing reductions in watershed nutrient inputs from the Branch & Derby Drain which empties into Paw Paw Lake near this basin.

Phase II would involve either a second alum treatment in the central deep basin similar to the approach applied in Phase I (in the deeper zone greater than 40-foot depth) at an approximate cost of $520,000 and an expected duration of effectiveness of 15-25 years **or** the implementation of an engineered hypolimnetic oxygenation system to address anoxic conditions below the thermocline at the second-most nutrient enriched basin (Station 2, Figure 9) in the central deepest portion of Paw Paw Lake. The oxygenation technology to be implemented for this portion of the plan is currently being developed and adapted to reduce or eliminate the need for shipping oxygen to the lake. Also, this option may potentially require supplemental iron or manganese additions to provide suitable substrate for phosphorus adsorption and settling. The range of capital cost for this hypolimnetic oxygenation system would be between $480,000 and $900,000 and yearly operation and maintenance costs would range between $12,000 and $25,000 (if iron and manganese additions are required). Either of these options for Phase II would also require public hearings for approval and financing.

The southern most deep basin (Station 1, Figure 9) does not currently have a significant influence (because of its smaller area and lower phosphorus concentrations below the thermocline) on internal phosphorus loading to Paw Paw Lake and does not warrant mitigation efforts at this time. It should be noted that other phosphorus mitigation and nutrient reduction options for Paw Paw Lake are being explored and are outside of the scope of this report. These alternative phosphorus mitigation options may be presented separately at a future date.

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APPENDIX A

Barr Engineering Sediment Coring Technical Memorandum

Technical Memorandum

To:	**Paul Hausler, Progressive Companies**
From:	Joe Bischoff, Senior Aquatic Ecologist
Subject:	Kate Lucas, Aquatic Ecologist
Date:	Paw Paw Lake Sediment Assessment
Project:	May 15, 2025
	Barr Project # 22111039.00

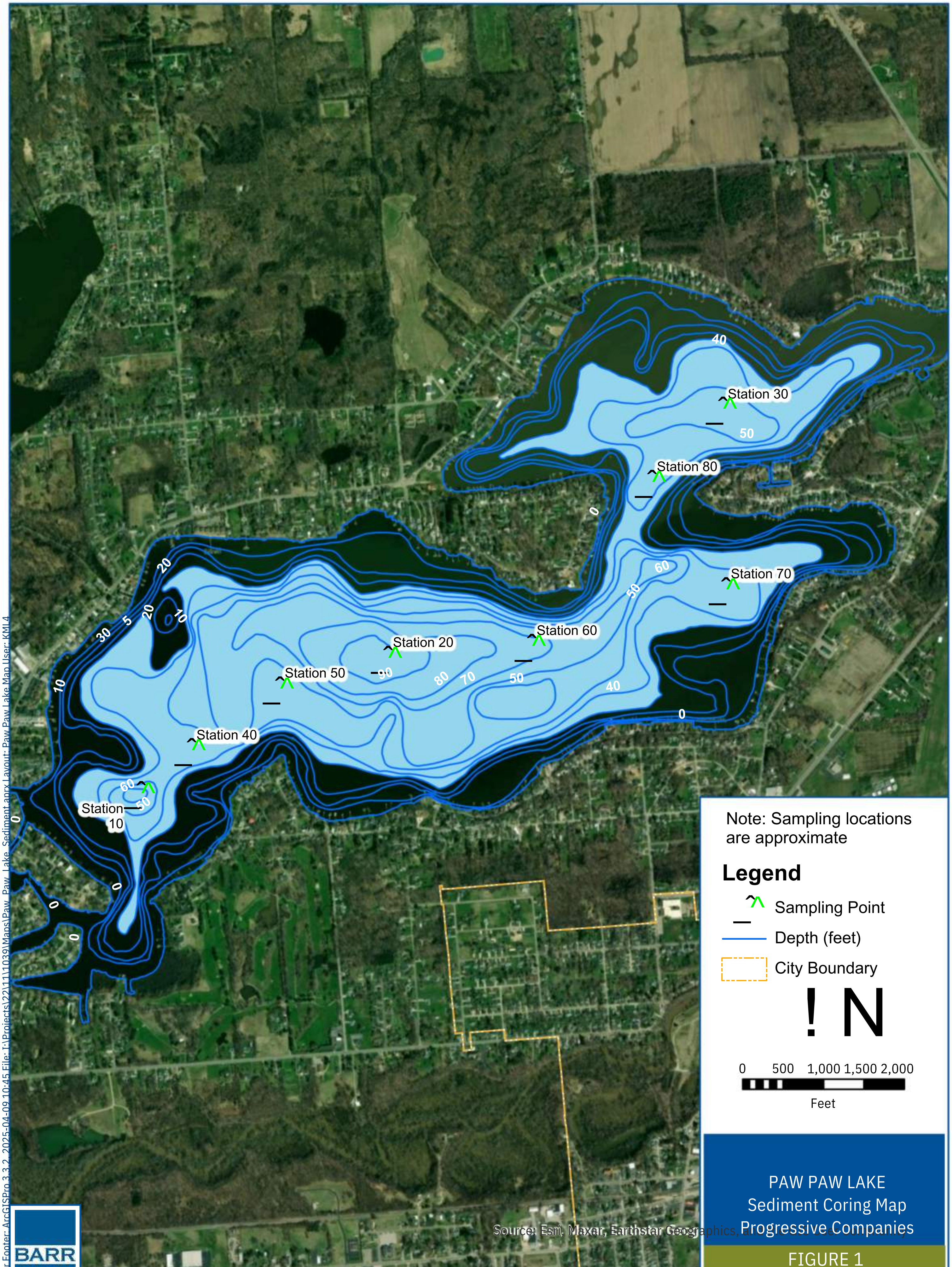
1 Background

Paw Paw Lake is a 922-acre lake located in Berrien County, Michigan with an average depth of 32 feet and a residence time of 776 days. Paw Paw Lake is considered dimictic, which means it stratifies during the warm summer period and creates low oxygen conditions in the hypolimnion (bottom layer of a stratified lake). Water quality monitoring data provided by Progressive Companies shows high levels of total phosphorus in the hypolimnion, with some values exceeding 375 µg/L at deep sampling points. Due to these elevated phosphorus levels, internal phosphorus loading was assessed to determine its impact on the lake's water quality. This technical memorandum aims to summarize the current status of internal phosphorus loading in Paw Paw Lake based on avaialble data and discusses whether an alum treatment would be a suitable approach to reduce phosphorus release from sediments and improve water quality.

2 Field and Laboratory Methods

Sediment cores were collected from locations on Paw Paw Lake, MI on October 21, 2024 (Figure 1). A gravity sediment coring device (Aquatic Research Instruments, Hope ID) equipped with an acrylic core liner was used to collect sediment cores. At Stations 10, 20, and 30, one core from each location was sectioned vertically at 2-cm intervals over the upper 10-cm and sectioned at 5-cm intervals between 10-25 cm to evaluate sediment chemistry. At all other stations, sediment cores were sectioned vertically at 5-cm intervals between 0-25 cm. All sediment sections were analyzed in the laboratory for mobile phosphorus fractions (loosely-bound P, iron-bound P, labile organic P), as well as the inactive Al-bound P fraction. Total iron and aluminum were also analyzed.

Three replicate cores at Stations 10, 20, and 30 were collected and incubated in the laboratory under anoxic conditions to determine sediment P release rates. Redox conditions were controlled by gently bubbling nitrogen (anaerobic) in the overlying water column throughout the 15-day incubation. Rates of sediment P release (mg/m2/day) were calculated using three methods. The first method quantifies the linear change in soluble reactive phosphorus (SRP) mass in the overlying water column divided by time (days) and surface area (m2) of the sediment. The second method uses a regression analysis from the beginning to the end of the experiment to estimate release rates. The final method uses a regression analysis for the period of greatest change to determine the maximum sediment P release rate.



PAW PAW LAKE
Sediment Coring Map
Progressive Companies

FIGURE 1

3 Water Quality and Internal Phosphorus Load

Surface Water Quality and Algae Blooms

Water quality data collected July through October 2024 provided by Progressive Companies was reviewed as a part of this assessment to evaluate internal phosphorus loading in Paw Paw Lake (Table 1). Surface total phosphorus and chlorophyll-a concentrations are relatively low in Paw Paw Lake suggesting the lake is moderately productive. A comparison of Paw Paw Lake to other inland lakes in Michigan using the EPA's National Lake Assessment classifies Paw Paw Lake as mesotrophic or moderately productive lake with good water clarity. In fact, Secchi depth was measured between 8 and 9 feet in Paw Paw Lake during the most productive part of the growing season.

Table 1. Water quality (July through October 2024) in Paw Paw Lake.

Station	Avg Surface TP (µg/L)	Avg Surface SRP (µg/L)1	Avg Surface Chlorophyll-a (µg/L)1	Avg Secchi Depth (ft)
10	19	10	2.0	8.9
20	16	10	2.8	8.6
30	13	10	2.5	8.1

1 Chlorophyll-a between 2 and 7 ug/L and total phosphorus between 10 and 20 ug/L are considered mesotrophic (moderately productive) conditions based on results from the National Lake Assessment (USEPA 2016b; USEPA 2016a).

However, Paw Paw Lake has a recent history of verified cyanobacteria blooms with at least 1 event exceeding World Health Organization microcystin thresholds (8 µg/L) for potential human health impacts (Table 2). So, even though total phosphorus concentrations are relatively low, enough nutrients exist in the lake to drive concerning cyanobacteria blooms. This can often be the result of internal phosphorus loading where high phosphorus concentrations in the hypolimnion provide a source of phosphorus to cyanobacteria species that can regulate their buoyancy. Some cyanobacteria species can migrate to deeper bottom water to obtain nutrients and then migrate back into high light conditions for growth. So, some lakes may appear to have good water quality, but internal loading may be driving potentially harmful algal blooms. This appears to be the case for Paw Paw Lake.

Table 2. Dates of confirmed cyanobacterial blooms in Paw Paw Lake.

Date	Cyanobacteria Present	Microcystin Test Strip Result (µg/L)
6/14/2023	Yes (verified)	< 1
10/1/2023	Yes (verified)	>10
8/7/2024	Yes (verified)	Not sampled

Paw Paw Lake strongly stratifies at each of the deep locations in the lake (Stations 10, 20, and 30) with late summer anoxia (<2 mg/L dissolved oxygen) as shallow as 20 feet in depth (Attachment A). Anoxic overlying water leads to reducing conditions in lake sediments resulting in the release of phosphorus bound to iron and manganese, and this is a primary driver of sediment phosphorus release in lakes. Total and soluble reactive phosphorus concentrations increase sharply below the thermocline, with maximum concentration exceeding 900 µg/L at Station 30 at the north end of the lake (Attachment A). Hypolimnetic phosphorus concentrations ranged between 250 ug/L and 400 ug/L at Stations 10 and 20 (Attachment A).

Phosphorus at all three stations was dominated by soluble reactive phosphorus suggesting that the build up is the result of anoxic sediment phosphorus release rather than phosphorus settling from surface waters.

Sediment Phosphorus Release

Sediment phosphorus release rates in Paw Paw Lake are relatively high compared to lakes in the Upper Midwest and the rates correlate with elevated hypolimnetic TP concentrations (Table 3; Figure 2). This suggests that internal phosphorus loading is contributing to the increased nutrient levels in the bottom waters and potentially influencing water quality throughout the lake. Station 30 demonstrated a potential maximum release rate of 16 mg/m2/day suggesting that sustained anoxia can result in large phosphorus loads coming from the sediments.

Table 3. Sediment P Release Rates (Mass change method) & Hypolimnetic TP Concentrations

Station	Avg P Release (mg SRP/m2/day)	Avg Hypolimnetic TP (ug/L)	Avg Hypolimnetic SRP (ug/L)
10	6.2	99	77
20	10.4	180	153
30	11.0	316	284

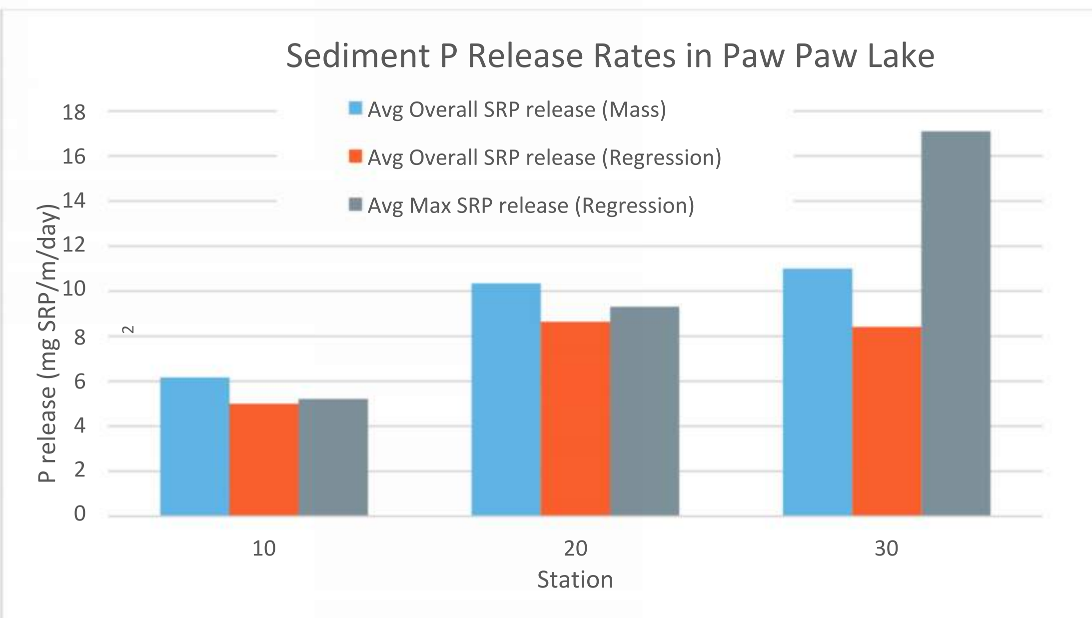


Figure 2. Experimentally derived sediment P release rates at three locations in Paw Paw Lake. Three methods were used to calculate sediment P release.

4 Sediment Chemistry and Aluminum Sulfate (Alum) Dosing

To assess the drivers of sediment P release in Paw Paw Lake and to develop an alum dose for Paw Paw Lake, the lake was divided into three distinct zones. Zone 1 includes the southern end of the lake

(Station 10) characterized by a 60-foot-deep spot with no major tributaries entering this part of the lake (Figure 3). Zone 2 includes the main body of the lake including one major tributary that flows through Little Paw Paw Lake. Zone 3 includes the northern area of the lake that receives drainage from approximately two-thirds of the watershed including two main tributaries, Sherwood Drain and the Branch & Derby Drain. The Paw Paw Lake outlet is located on the southernmost shore south of Zone 1, resulting in much of the watershed drainage passing through and settling out solids in Zones 3 and 2 and eventually passing through Zone 1.

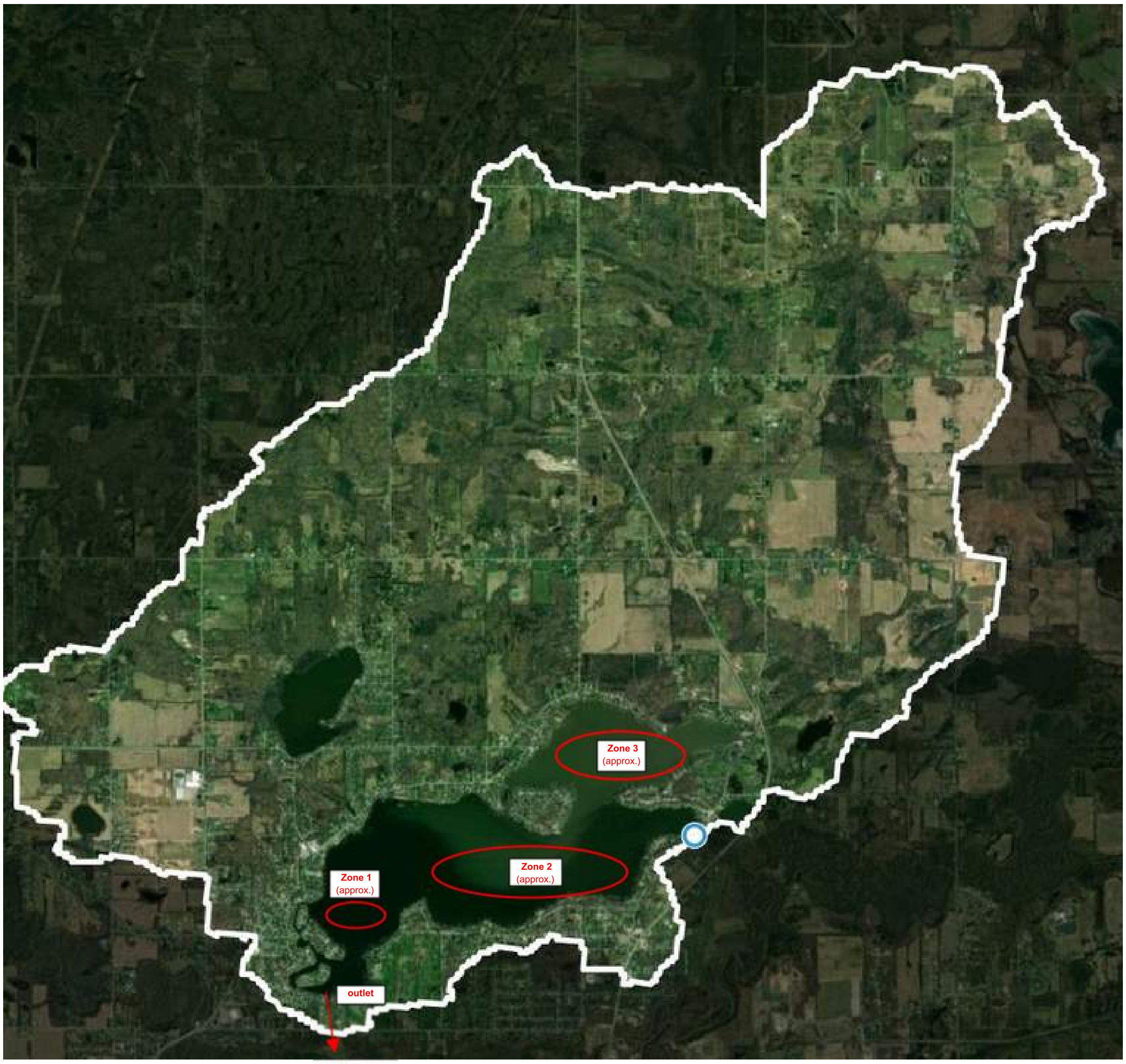


Figure 3. Estimated watershed area for Paw Paw Lake (41.7 km2) using nationally available digital elevation models provided at modelmywatersehd.org.

To determine sediment P dynamics in Paw Paw Lake sediments were analyzed for P fractions. Redox-P, which includes iron-bound and loosely-bound P, is the fraction of phosphorus most associated with sediment P release during periods of low dissolved oxygen (<2 mg/L) at the sediment water interface. Labile organic P can be released in all conditions (high and low dissolved oxygen) as organic material is decomposed.

Zone 1

Zone 1 represents the southern area of the lake with no major inflows in this basin. Redox-P was relatively low in the southern deep area (Station 10) in Paw Paw Lake with redox-P concentrations less than 0.2 mg/g (Figure 4). For context, redox-P concentrations less than 0.2 mg/g in Minnesota lakes is typically associated with lower P release in lakes with less impacted or developed watersheds. Station 40 representing the shallower areas in the southern part of the lake, was also low in redox-P. Station 10 and Station 40 had elevated labile organic P, suggesting sediment decomposition may contribute to sediment P release. Sediment phosphorus release was lowest in Zone 1 (6 mg/m2/day) and had the lowest average hypolimnetic phosphorus concentrations (99 µg/L).

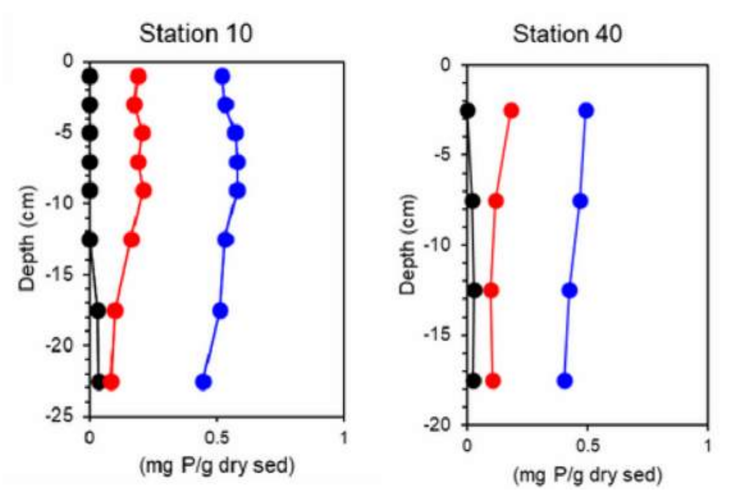


Figure 4. Phosphorus fractions profiles in Zone 1 Paw Paw Lake sediment at Station 10 (deep hole) and Station 40. The black line is loosely bound P, red line is iron bound P, and the blue line is labile organic P.

Zone 2

Zone 2 is the main basin of the lake receiving drainage from Little Paw Paw Lake through the Sherwood Drain. Stations 20 (deep spot), 50 and 60 (between 50 and 60 feet), and 70 (between 40 and 50 feet) were sampled to characterize sediment chemistry in the main basin of the lake. Station 20 was relatively high in redox-P reaching almost 0.5 mg/g in the upper 5-cm of sediment (Figure 5). Sediment P release was also relatively high at 10 mg/m2/day with hypolimnetic phosphorus concentration averaging around 180 ug/L. Stations 50 and 60 also had elevated redox-P concentrations in the upper 5 to 10-cm of sediment. The easternmost and shallowest station (Station 70) had the lowest redox-P concentrations in Zone 2. Labile organic P was similar in all 4 stations with concentrations near 0.5 mg/g.

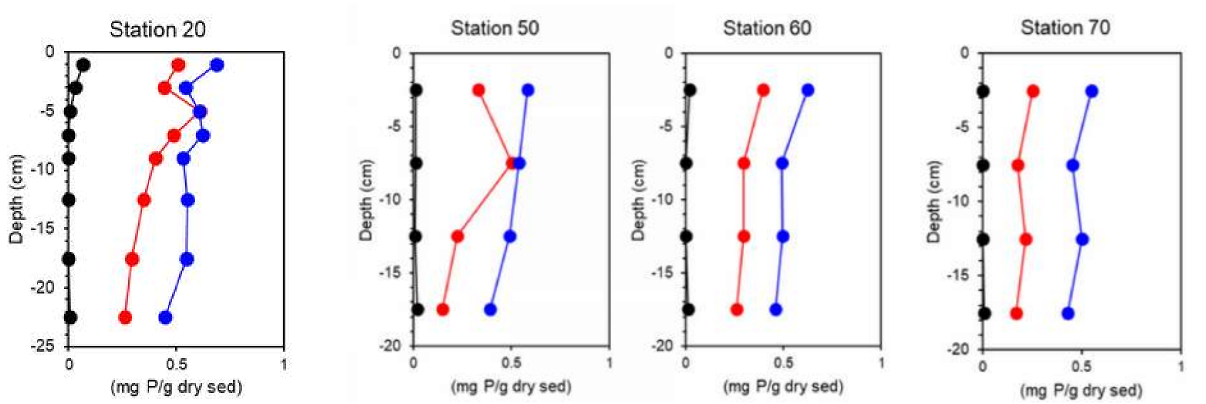


Figure 5. Phosphorus fractions profiles in Zone 2 Paw Paw Lake sediment at Station 20 (deep hole) and Stations 50, 60, and 70. The black line is loosely bound P, red line is iron bound P, and the blude line is labile organic P.

Zone 3

Zone 3 receives the largest drainage area. The outlet to the lake is on the east side of the lake between Zones 2 and 3. The configuration of the lake and location of inflows and outlet suggests that some of the inflows may bypass the central and southern basins of the lake. Station 30, which represents the deep location in Zone 3 had the highest sediment P release at 11 mg/m2/day and the highest average hypolimnetic P concentrations at 316 ug/L. Redox-P at Station 10 was relatively high in the upper 5-cm and remained high deep into the sediment profile (Figure 6). In contrast, the shallower Station 80 (40 to 50 feet in depth) was much lower in redox-P. Both locations had similar labile organic P concentrations.

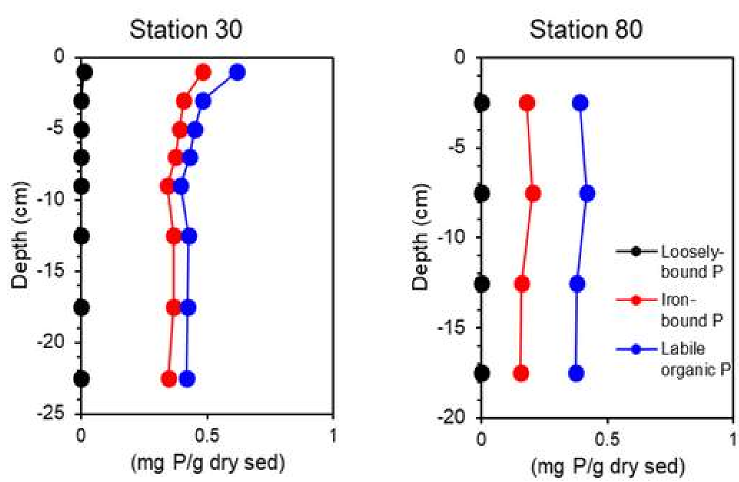


Figure 6. Phosphorus fractions profiles in Zone 3 Paw Paw Lake sediment at Station 30 (deep hole) and Station 80. The black line is loosely bound P, red line is iron bound P, and the blude line is labile organic P.

5 Potential Alum Application Strategies and Preliminary Cost Estimates

While Paw Paw Lake exhibits relatively good surface water quality, it also has a history of cyanobacteria blooms with at least one verified toxic event in October of 2023. This may be a result of high phosphorus concentrations in the hypolimnion (bottom water) resulting from sediment phosphorus release. Some cyanobacteria can regulate their buoyancy, allowing them to access phosphorus rich bottom waters and high light surface waters. Minimizing total phosphorus in bottom waters through an alum treatment program may be an option to help alleviate these potentially harmful cyanobacteria blooms.

Two primary factors are typically considered when determining area(s) to treat with alum including redox-P concentrations in the sediment profile and the average depth of anoxia.

Data collected from 2023 and 2024 show the minimum anoxic depth (< 2 mg/L DO) in Paw Paw Lake is around 20 feet. However, available data demonstrate that hypolimnetic phosphorus concentrations only increase between 30 and 40 feet suggesting that the deeper sediments are contributing more phosphorus to the hypolimnion than the shallower sediments. These results suggest generally targeting areas greater than 40 feet in depth, rather than simply using the anoxic area (>20 feet in depth), is likely to be most cost-effective approach for a potential alum treatment program. It should be noted that the entire area below 40 feet does not need to be treated with alum. Rather this area us used as a starting point and then is adjusted using sediment chemistry data and professional experience.

Using the data and observations presented in this memo, including the redox-P profiles, four preliminary alum application zones were identified, and individual alum doses were estimated for each of the potential application zones (Table 4, Figure 7). Each zone includes areas with high redox-P in surficial sediments, consistent anoxia throughout the summer, and depths greater than 40 feet.

Table 4. Alum dose and application areas

Zone	Alum Dose g Al/m2	Target Sediment Depth (cm)	Treatment Area (acres)
1	80	6	20
21	100	5	134
2 (deep)	126	8	69
3	187	8	51

[1] Deep area subtracted from the total area

Alum treatments require maintaining a pH above 6 and below 9 to prevent solubilization of the aluminum and potential toxic impacts on lake biota. Titrations were completed using lake water to determine if the application requires using a buffered aluminum application. Lake aluminum concentrations can reach 13.9 mg/L before pH will drop below 6. All of the evaluated scenarios discussed in this memo are expected to result in aluminum concentrations below that, suggesting that buffering is not required. However, future doses should be evaluated on a case-by-case basis. Other permitting requirements may need to be considered such as aluminum water quality standards.

To support project feasibility assessment and planning, a planning level cost estimate for an alum treatment was developed (Table 5) using the above scenarios for alum dosing. Unit costs were based on recent alum applications completed in the Minnesota Twin Cities Metropolitan Area. Since most alum applications are split into several applications, monitoring was included in the estimates to allow for the treatments to be completed adaptively. Since alum (aluminum sulfate) is a commodity and prices are subject to rapid change, a 20% contingency is included in the overall cost estimate. Using this approach, an alum treatment could more than $2.7 million dollars for Paw Paw Lake. However, alum treatments are recommended to be implemented adaptively, applying the total estimated dose over several applications typically 2 to 3 years apart (which could add cost to the overall total but also allow costing to be spread overall several years). Further, since Paw Paw Lake demonstrates relatively good surface water quality except for periodic cyanobacteria blooms, an adaptive approach is recommended to focus on the mitigation of these cyanobacteria blooms. It may be that the cyanobacteria blooms can be eliminated with a lower dose. An adaptive approach allows an opportunity for dialing in the dose based on year-to-year observations and monitoring data to optimize dosing and enhance cost-effectiveness of treatment.

One potential approach is to target the deep locations (Stations 10, 20, and 30) to minimize phosphorus build up in the hypolimnion recognizing that not all sediment P release will be addressed. This involves applying to Zones 1, 2 (deep) and 3 reducing the applied alum costs by more than $700,000. Further, since Zone 1 (Station 10) showed minimal mobile phosphorus build up, focusing on Zones 1 and 2 (deep) could significantly reduce cyanobacteria blooms and reduce costs. These approaches require flexible planning and recognition that the outcomes are not certain and future larger applications may be required and could require the overall dose provided in this memo. We often recommend the implementing agency be prepared to implement the full dose but use the adaptive process to determine if smaller dose areas can meet water quality objectives but recognize the full dose might be required. Further discussion of the risks and potential outcomes is required before a final scenario is identified.

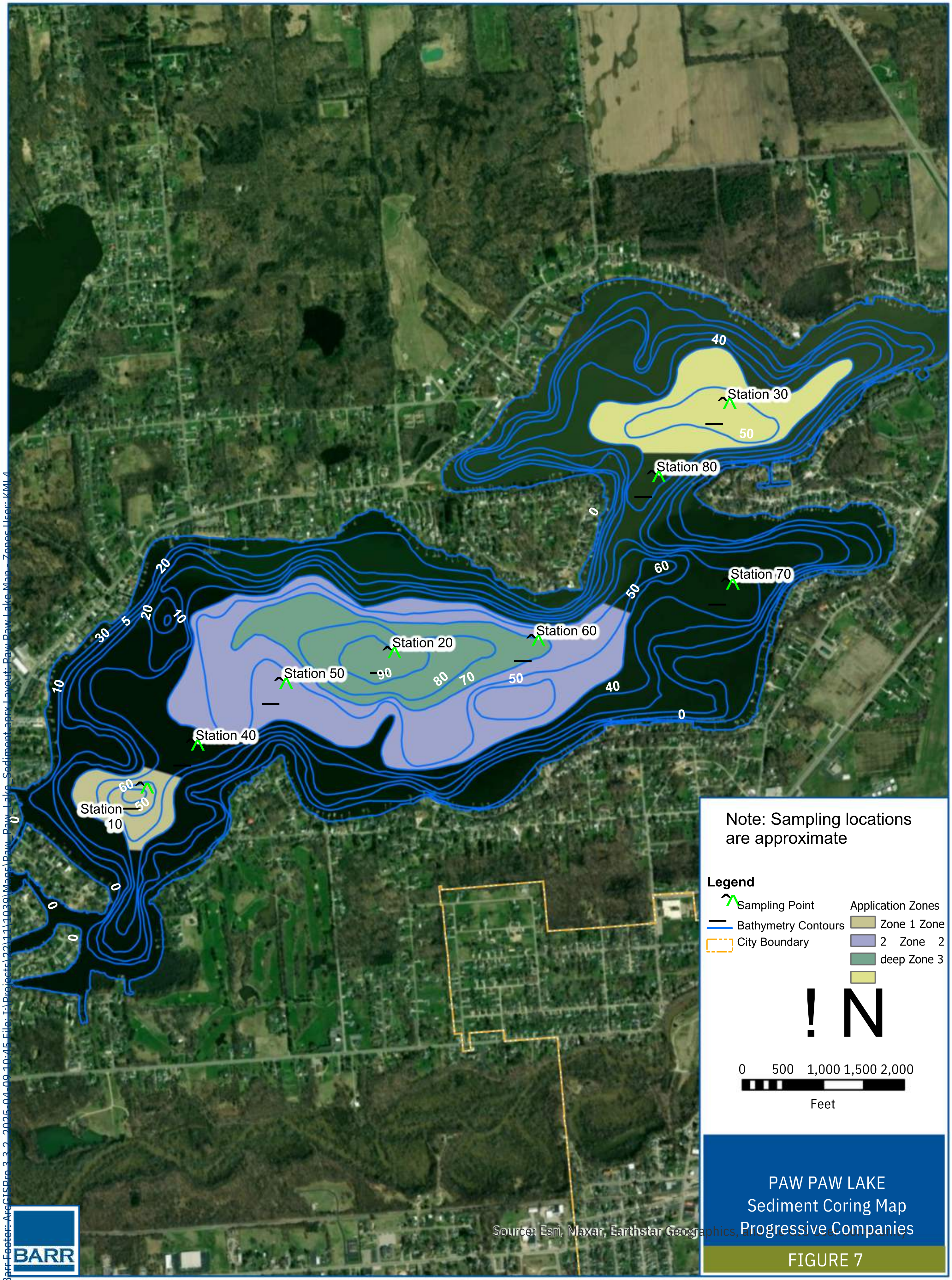

Station 30
Station 80
Station 70
Station 60
Station 20
Station 50
Station 40
Station 10
40
50
60
70
80
90
30
20
10
5
0
Note: Sampling locations are approximate
Legend
Sampling Point
Bathymetry Contours
City Boundary
Application Zones
Zone 1
Zone 2
deep Zone 3
N
0 500 1,000 1,500 2,000
Feet
PAW PAW LAKE
Sediment Coring Map
Progressive Companies
FIGURE 7
Source: Esri, Maxar, Earthstar Geographics
BARR

Table 5. Planning level cost estimate for treating areas with high redox-P with aluminum sulfate.

Zone	Acres	Item	Unit	Quantity	Unit Cost	Total Cost
1	20	Aluminum sulfate	Gal $Al_2(SO_4)_3$	29,088	$2.90	$72,720
2	134	Aluminum sulfate	Gal $Al_2(SO_4)_3$	244,781	$2.90	$611,953
2 (deep)	69	Aluminum sulfate	Gal $Al_2(SO_4)_3$	158,657	$2.90	$396,643
3	51	Aluminum sulfate	Gal $Al_2(SO_4)_3$	173,865	$2.90	$434,663
		Mobilization[1, 2]	Lump Sum (~20%) / each mob	3	$100,000	$300,000
		Monitoring[2] (3 events)	Lump Sum / each treatment	3	$35,000	$105,000
		Plans and Technical Specifications[2]	Lump Sum	1	$30,000	$30,000
		Application Observation	Lump Sum	3	$15,000	$45,000
		Contingency[1, 2]	-	20%	-	$400,000
		Total Application Cost[1,3]	-	-	-	$2,400,000

[1] Costs rounded
[2] Allocation
[3] Excludes modeling, refinement of dosing, permitting, stakeholder engagement, bidding, special compliance requirements, and long-term post implementation monitoring/reporting.

Barr's opinion of probable cost is a screening level cost estimate for the purposes of screening and evaluating technology feasibility. Quantities are approximate. Unit costs noted are based on Barr's experience on projects implemented in Minnesota. Actual costs will be a function of product availability and costs, as well as trucking costs, which will be a function of project travel distance. For increased confidence in pricing, Barr recommends obtaining preliminary quotes from qualified vendors/contractors likely to implement a treatment program. Finally, further investigation of the Paw Paw Lake phosphorus budget is recommended prior to implementing a project of this size. Typically, a lake response model and phosphorus budget are developed to better understand phosphorus sources and to determine overall contribution of internal loading. Since hypolimnetic P is hypothesized to be a driver of the cyanobacteria blooms, it is also prudent to collect a full season of water quality data (total phosphorus, chlorophyll-a, and Secchi) as well as cyanobacteria counts since chlorophyll-a is a poor indicator of cyanobacteria. More detailed monitoring will help verify the role of internal loading on the cyanobacteria blooms.

6 References

MI DEQ. Michigan's State Level Assessment of the 2012 National Lakes Assessment Project: Comparisons with National and Regional Results. Report MI/DEQ/WRD-17/011.

USEPA. 2016a. "National Lakes Assessment 2012: A Collaborative Survey of Lakes in the United States. EPS 841-r-16-113. U.S. Environmental Protection Agency, Washington, DC. https://nationallakesassessment.epa.gov/."

USEPA. 2016b. "National Lakes Assessment: Technical Report. EPA 841-R-16-114."

APPENDIX B

Spring 2024 Paw Paw Lake Water Quality Data

TABLE 1 - PAW PAW LAKE 3/25/2024 DEEP BASIN WATER QUALITY DATA

Date	Station	Sample Depth (feet)	Temperature (F)	Dissolved Oxygen (mg/L)*	Total Phosphorus (µg/L)*
25-Mar-24	1	1	42.0	12.6	14
25-Mar-24	1	10	42.0	12.6	25
25-Mar-24	1	20	42.0	12.5	18
25-Mar-24	1	30	42.0	12.5	18
25-Mar-24	1	40	42.0	12.4	10
25-Mar-24	1	50	42.0	12.3	10
25-Mar-24	1	57	42.1	12.2	16
25-Mar-24	2	1	42.0	12.8	14
25-Mar-24	2	10	42.0	12.8	<10
25-Mar-24	2	20	42.1	12.7	11
25-Mar-24	2	30	42.0	12.7	14
25-Mar-24	2	40	42.0	12.7	15
25-Mar-24	2	50	42.0	12.7	16
25-Mar-24	2	60	42.0	12.7	13
25-Mar-24	2	70	42.0	12.6	11
25-Mar-24	2	80	42.0	12.6	17
25-Mar-24	2	87	42.0	12.6	11
25-Mar-24	3	1	42.1	12.7	14
25-Mar-24	3	10	42.1	12.7	11
25-Mar-24	3	20	42.1	12.7	11
25-Mar-24	3	30	42.1	12.7	11
25-Mar-24	3	40	42.1	12.6	12
25-Mar-24	3	53	42.2	12.6	17

TABLE 2 - PAW PAW LAKE 3/25/2024 SURFACE WATER QUALITY DATA

Date	Station	Secchi Transparency (feet)	Chlorophyll-*a* (µg/L)*
25-Mar-24	1	6.5	4
25-Mar-24	2	7.0	3
25-Mar-24	3	6.0	4

* mg/L = milligrams per liter = parts per million
* µg/L = micrograms per liter = parts per billion