ALUM TREATMENT PLAN

Lake Kanasatka

Moultonborough, NH

January 2024

Prepared by

Laura Diemer, CLM
FB Environmental Associates

NH Department of Environmental Services
Watershed Management Bureau
29 Hazen Drive, PO Box 95
Concord, NH 03302-0095

January 12, 2024

Dear Mr. Neils,

On behalf of the Lake Kanasatka Watershed Association (LKWA), we submit the following alum treatment plan to reduce the internal phosphorus load and minimize the likelihood of potentially toxic cyanobacteria blooms for Lake Kanasatka, Moultonborough, NH.

Under RSA 485-A:13, I(a), Water Discharge Permits, and N.H. Code of Administrative Rules Chapter Env-Wq 300, Surface Water Protection, the following alum treatment plan serves as the permit application to NHDES for the authorization to discharge aluminum sulfate (alum) and sodium aluminate to Lake Kanasatka to control the growth of cyanobacteria by inactivating mobile phosphorus in surficial sediments.

As the permittee, LKWA agrees to comply with state water quality standards, visual and ambient water quality monitoring, recordkeeping, and post treatment reporting to NHDES.

Sincerely,

Laura Diemer, CLM
FB Environmental Associates
laurad@fbenvironmental.com
(603) 828-1456

cc: Kirk Meloney, LKWA President

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Lake Kanasatka suffers from excessive internal phosphorus loading (representing 20% of the total phosphorus load) that has been causing the persistence of cyanobacteria blooms throughout the recreational season each year since 2020 (Figure 1). Water quality analyses and modeling through planning efforts conclude that a combination of external and internal phosphorus load reduction measures, totaling at least 48 kg/yr of phosphorus, is needed to fully restore Lake Kanasatka.

Several management techniques with varying levels of effectiveness, longevity, cost, risk, and effort exist to address cyanobacteria blooms. For evaluating applicability to Lake Kanasatka, strong preference was given to techniques that reduce phosphorus loading as the primary source of nutrition supporting cyanobacteria growth. Recommended management techniques with the greatest applicability for Lake Kanasatka include 1) external phosphorus load reduction through nonpoint source controls and pollutant trapping and 2) phosphorus inactivation in surficial sediments. Reducing the external phosphorus load extends the longevity of a phosphorus inactivation approach and is thus the primary recommendation for sustainable restoration of Lake Kanasatka. See further discussion below.

The proposed project uses a phosphorus inactivation approach to bind phosphorus in surficial sediments through the application of aluminum as aluminum sulfate (alum) and sodium aluminate (aluminate). **The final alum treatment plan recommendation for Lake Kanasatka is to apply a total areal dose of 55 g/m^2 over a treatment area of 153 acres representing 7.5 m and deeper in spring 2024.** The areal dose will be applied in multiple doses of 25 g/m^2 or less at least one day apart in any given zone and at an alum:aluminate ratio of 2:1 to minimize aluminum toxicity risks to aquatic organisms. The cost of this treatment is estimated to be $453,900, not including monitoring or outside consulting assistance. An internal load reduction of ~80% can be expected with phosphorus inactivation. This is a one-time treatment over a few days in spring that typically lasts more than 10-20 years, depending on the sedimentation rate of the waterbody and the effectiveness of external phosphorus load reduction efforts. This technique has proved successful in many lakes throughout the country and has been used recently in one New Hampshire lake (Nippo Lake in Barrington) and several Maine lakes (e.g., Long Pond in Parsonsfield, East Pond in Oakland, and Lake Auburn in Auburn).

Following the spring 2024 treatment, we recommend that monitoring be completed each summer according to the monitoring plan to assess the efficacy of the alum treatment over time. If the efficacy of the alum treatment degrades sooner than expected, then **we recommend a second alum treatment be applied at an areal dose of 25 g/m^2 over a treatment area of 153 acres representing 7.5 m and deeper in spring** (though additional sediment samples should be collected to confirm the calculated dose for a possible second treatment). The second treatment would treat the labile organic phosphorus fraction not directly targeted in the first treatment. The general practice for alum treatments is to split the dose if it is relatively high, which for New England tends to fall within 50 to 75 g/m^2, and wait a year or more in-between treatments. This approach allows the first treatment to be more affordable, lowers the risk to aquatic organisms in both treatments, and allows the additional dose in the second treatment to be more effective than if combined with the first treatment. The second treatment strips the water column of phosphorus for a second time and treats newly settled phosphorus from the external load or newly decayed phosphorus in the sediment since the first treatment.

Immediate water quality improvements can be expected following the alum treatment of Lake Kanasatka. The alum floc strips phosphorus from the water column as it migrates down to the sediment where it binds with mobile phosphorus. In the first summer assuming a non-extreme weather year, Lake Kanasatka will likely experience record high water clarity and minimal to no cyanobacteria accumulations or blooms from the reduction in available phosphorus. In the long-term according to model prediction scenarios, total phosphorus concentration will decrease, water clarity will deepen, and bloom probability will be substantially curtailed. Overall, through the significant reduction of cyanobacteria biomass, alum treatments have been shown to shift biological communities in favor of more balanced food webs. The reduction in cyanobacteria biomass that dies and settles in the sediment can lessen oxygen demand and might help to decelerate the expansion of anoxic area in Lake Kanasatka, further benefiting treatment longevity. Better water clarity following treatments has also increased aquatic plant growth in littoral areas, so careful watch for invasive species is important.

Advancements in treatment technology over time have greatly improved the safety and efficacy of treatments, which are now considered a proven in-lake management option for internal phosphorus load control. Through careful application, minor short-term impacts to aquatic life following an alum treatment are considered an acceptable trade-off for the massive ecological disruptions and health concerns caused by recurrent cyanobacteria blooms.

It is important to understand that alum treatments are temporary management measures to control internal phosphorus loads that come from legacy external phosphorus loads. Without substantial reductions in the external phosphorus loads, phosphorus will continue to build up in newly deposited sediment and begin to release again as internal phosphorus load. Thus, the expected water quality improvements will deteriorate over time until the internal phosphorus load returns to pre-treatment magnitude. The alum treatment longevity for Lake Kanasatka will likely be shorter than other alum treatments performed on deep stratified lakes in Maine and New Hampshire given its unique characteristics. Hypervigilance to continually reduce the external phosphorus load to Lake Kanasatka will be critical to maximizing the alum treatment's effective lifespan.

To permit an alum treatment, NHDES required LKWA to document an external phosphorus load reduction of 10 kg/yr. LKWA has met that goal through tireless work addressing priority sites identified in the Watershed-Based Management Plan. LKWA enlisted the help of 53 volunteers to complete projects such as installing drainage ditches and water razors and stabilizing pathways around the watershed in 2023. Two volunteers donated considerable time using their large tractor/loader/backhoe and small tractor/loader. One volunteer completed 21 consultations for using rubber razors to divert runoff which resulted in 16 installed razors, not including five that were installed on Camp Quinebarge property. Another volunteer completed 18 consultations with property owners and completed 12 projects. Sixteen (16) shorefront properties around Lake Kanasatka have become LakeSmart certified since 2019, with six awarded in 2022 and seven awarded in 2023. At the request of LKWA, the Moultonborough Public Works Director completed grading of Glidden Road and added stone swales to Red Hill Rd in 2023. Due to persistent communication from LKWA, the NHDOT and NHDES Bureau of Dams are in progress to renovate the boat launch/dam area and have ceased dumping/plowing snow at the dam. NHDOT also completed improvements to Route 25 that have reduced sediment loading to the lake. Ten (10) septic system upgrades were documented around the lake since 2021, with two more planned. LKWA also successfully applied for 319 Watershed Assistance Grant program funding to remediate two BMP sites along Burton Rd as identified during the watershed survey as part of the Watershed-Based Management Plan. A summary of the completed work can be found in Table 3 of the following report.

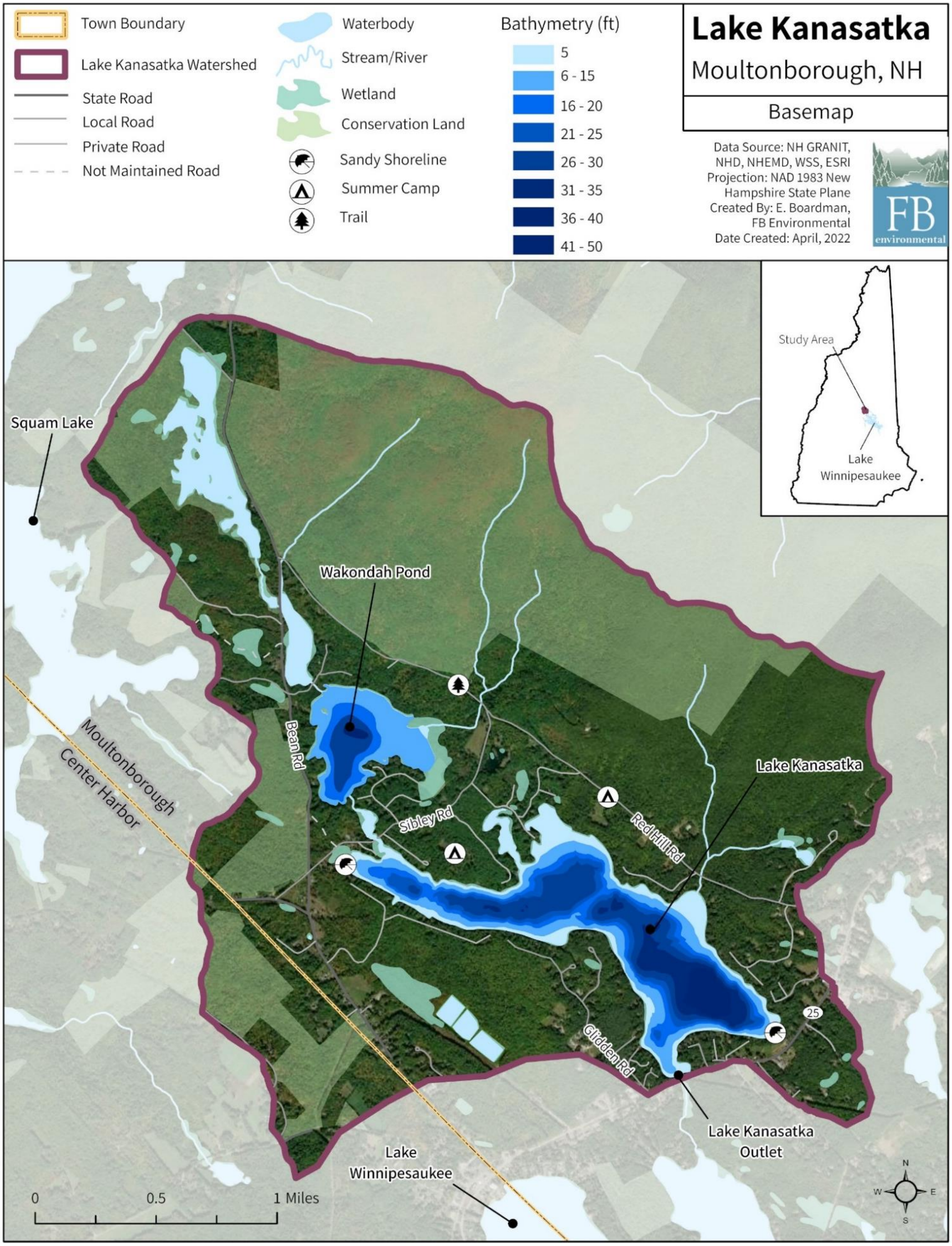

Figure 1. Lake Kanasatka watershed.

PROBLEM BACKGROUND

Lake Kanasatka is a 143-hectare (353-acre) oligotrophic lake with 5.2 miles of shoreline, a maximum depth of 14 meters (46 feet), and a volume of 8,344,010 cubic meters (Figure 1). The areal water load is 5.9 meters/yr (19.4 feet/yr), and the flushing rate is around or just slightly more than once per year. The watershed, not including the lake area, spans 1,690 hectares (4,176 acres) in Moultonborough and Center Harbor, NH (Figure 1). Lake Kanasatka is fed by upstream waterbodies including Wakondah Pond as well as several tributaries such as Kanasatka Brook, Red Hill Stream, and Jennifer's Path Stream. Wakondah Pond is a 38-hectare (94-acre) lake connected to Lake Kanasatka by an unnamed tributary, which flows 268 meters (879 feet) upstream from the Sibley Road crossing at the northwestern end of Lake Kanasatka. From the dammed outlet of Lake Kanasatka at the southern end of the lake, water flows 579 meters (1,869 feet) south via an unnamed tributary[1] near Whittier Highway / NH Route 25 to Blackey Cove of Center Harbor in the economically vital Lake Winnipesaukee, just east of Center Harbor village.

The lake has public access near its dam along Route 25 and is surrounded by 164 shorefront homes and one business, an overnight summer camp operating since 1936. Many homeowners rent out their homes, serving as an income source for the residents and tax base for the town and state, contributing $800,000 annually in tax revenues. Lake Kanasatka is facing a significant cyanobacteria health crisis that has been growing since 2020 and threatens the health and safety of the residents, visitors, pets, and wildlife, including the loon population, and reduces safe recreational opportunities, income generation through rentals, and property values.

Water Quality

Lake Kanasatka has experienced generally good water quality through the years up until recent persistent whole-lake cyanobacteria blooms that have resulted in NHDES posting multiple advisories for extended periods of time each summer since 2020.

On the 2020/2022 NHDES Report Cards, Lake Kanasatka is reported as Category 3 Potentially Not Supporting (PNS) for Aquatic Life Integrity for two parameters: elevated total phosphorus and low pH. Given the recent bloom record, NHDES indicated that the next reporting cycle would likely assess Lake Kanasatka as impaired for Primary Contact Recreation due to cyanobacteria. Per the DES 2020/2022 CALM, a lake is considered non-supporting for Primary Contact Recreation if "*there is conclusive evidence that cyanobacteria blooms in the most recent ten-year period have occurred in amounts and for durations that significantly interfere with the primary contact recreational use*." DES indicates that factors such as the frequency and duration of documented blooms, the types of cyanobacteria and/or toxins present, and the frequency of department staff visits to the waterbody because of blooms are considered in the assessment determination.

NHDES issued four cyanobacteria bloom advisories over 2020 and 2021 in late summer (August and September) for periods ranging from seven to 15 days (Table 1). During their routine sampling of Lake Kanasatka, the University of New Hampshire (UNH) Lakes Lay Monitoring Program (LLMP) first alerted NHDES to a possible cyanobacteria bloom in early August 2020. All four bloom periods were lakewide except for the 9/29/20 bloom that was more localized with scum forming along the shorelines. The dominant taxa identified for each bloom in 2021 were determined from 32 samples collected by NHDES from seven areas around the lake, largely along the shoreline or at the Animal Island deep spot.

Lake Kanasatka was placed under two cyanobacteria bloom advisories by NHDES in summer 2022 (Table 1). The first advisory for 109,267 cells/mL with *Dolichospermum* as the dominant taxa lasted 13 days beginning on 7/29/22. NHDES described the bloom as "*appearing as wispy aggregations of light green specks…seen in several locations*

[1] NHDES Assessment Unit named "Kanasatka Lake Outlet Brook," assessment unit ID NHRIV700020105-05.

across the lake." NHDES also noted that other cyanobacteria (*Dolichospermum*, *Tolypothrix*, and *Calothrix*) were "*present in low densities from shoreline samples" and are "associated with benthic growth and do not form surface blooms but can produce toxins*." The second advisory for 1,375,600 cells/mL with *Dolichospermum* and *Aphanizomenon* as the dominant taxa lasted 79 days beginning on 8/29/22. NHDES described the bloom as "*appearing as bright clouds of material along shorelines…seen in several locations across the lake*."

Several cyanobacteria species were prominent throughout the 2020-22 summer seasons in Lake Kanasatka, most notably *Dolichospermum*, *Aphanizomenon*, *Planktothrix*, *Microcystis*, and *Woronichinia*, all of which are potentially toxic and produce both taste and odor. *Dolichospermum* and *Aphanizomenon* are both nitrogen fixers, preferring low nitrogen to phosphorus ratio waters where they can readily outcompete other species by fixing their own nitrogen for growth. *Planktothrix* reside in deeper waters around the thermocline and tend to make an appearance in late summer or early fall when mixing disturbs stratification in Lake Kanasatka. Lake Kanasatka is somewhat unique due to its high diversity of cyanobacteria compared to most lakes that may only have one or two dominant species. This is troubling from a public health perspective because the high diversity increases the probability that toxins are produced. Amanda McQuaid of UNH LLMP completed a 2020-22 summary report on Lake Kanasatka and Wakondah Pond, reviewing cyanobacteria species and cyanotoxin data. Cyanotoxins were present in concentrations above established thresholds on multiple days during the study period and represent a severe health risk to humans and wildlife.

Aerial image of the fall 2023 bloom in Lake Kanasatka (left) and Blackey Cove (right) in Center Harbor, Lake Winnipesaukee.

In 2023, Lake Kanasatka was under advisory from 6/2 to 6/16, 8/7 to 8/31, and 9/22 to 12/14, the latter hitting a record 83 days in duration (Table 1). The June bloom was reported by NHDES as having concentrations of *Dolichospermum* reaching 362,000 cells/mL. The August bloom was reported by NHDES as "*appearing as green clouds, surface streaks and accumulated specks*," with concentrations of *Dolichospermum* reaching 95,400 cells/mL. The bloom occurred "*lakewide throughout the top of the water column, creating low clarity but not necessarily forming surface scums everywhere*." The fall bloom was reported by NHDES as "*appearing as brown and green ribbons of accumulation along some shorelines, and flecks of material accumulating mid-lake. Samples collected and reviewed on 22 September had cyanobacteria (*Dolichospermum*,* Woronichinia *and* Microcystis*) in concentrations up to 608,460 cells/mL in areas of highest observed accumulations. A sample from mid-lake had a density of 16,334 cells/mL (*Dolichospermum *and* Woronichinia*). A plankton tow sample taken from 5 meters in the middle of the lake had high densities of* Dolichospermum, Woronichinia*, the chrysophytes* Chrysosphaerella *and* Synura*, and the diatoms* Tabellaria *and* Fragilaria*.*" Samples collected on 10/17/23, 11/5/23, and 11/15/23-11/30/23 showed concentrations of *Dolichospermum* and *Woronichinia* as high as 2,242,000 cells/mL, 2,134,000 cells/mL, and >3,000,000 cells/mL, respectively, with "*multiple reports of intense lakewide bloom conditions*."

Table 1. Cyanobacteria advisories issued by NHDES for Lake Kanasatka from 2020-23.

Advisory Date	**Duration (Days)**	**Dominant Taxa**	**Total Cell Concentration (cells/mL)**
8/12/2020	14	*Dolichospermum*	78,750
9/29/2020	10	*Microcystis, Aphanizomenon, Woronichinia, Dolichospermum*	393,500
8/4/2021	15	*Dolichospermum*	775,000
9/13/2021	7	*Dolichospermum*	500,000
7/29/2022	13	*Dolichospermum*	109,267
8/29/2022	79	*Dolichospermum*	1,375,600
6/2/2023	14	*Dolichospermum*	362,000
8/7/2023	24	*Dolichospermum*	95,400
9/22/2023	83	*Dolichospermum, Woronichinia and Microcystis*	>3,000,000

It is difficult to run meaningful trend analyses on historic data for Lake Kanasatka given the limited data collection frequency (generally one sample event per season for key parameters such as total phosphorus and chlorophyll-a). With the assistance of the UNH LLMP, LKWA collected more robust data in 2022 and 2023 to support data analyses in anticipation of this treatment plan. Only 2022 data were available and analyzed during development of this treatment plan to help elucidate seasonal trends in key parameters.

Total phosphorus concentrations from epilimnetic composite cores were consistent throughout the 2022 field season, ranging from 7.1 to 9.7 µg/L from 5/20/22 to 9/9/22, and increased to 12.2 µg/L on 9/21/22 and 14.2 µg/L on 10/7/22 following the breakdown of thermal stratification that mixed high phosphorus concentration bottom waters with surface waters (Figure 2). Chlorophyll-a concentrations from epilimnetic composite cores remained relatively low, ranging from 1.6 µg/L to 3.2 µg/L from 5/20/22 to 8/9/22, until concentrations steadily increased from 8/19/22 to 10/7/22 to a peak of 7.2 µg/L. In response to increasing chlorophyll-a concentrations, Secchi Disk Transparency readings steadily became shallower from 8/19/22 to 10/7/22 to a minimum of 4.1 meters. Generally, epilimnetic composite core chlorophyll-a concentrations and Secchi Disk Transparency readings did not indicate poor water quality conditions for the first bloom but did for the second which lasted the remainder of the season.

Thermal stratification at the deep spot (1 Deep) was set in by the first sample date on 5/20/22 and reached its peak by 8/9/22 with a maximum surface water temperature of 29.5 °C or 85.1 °F (Appendix A, Table A1). As air and surface water temperatures cooled heading into September, thermal stratification began breaking down with near complete mixing of the entire water column down to 12 meters depth (out of 13-13.5 meters) by 10/7/22. Anoxia (< 2 mg/L dissolved oxygen concentration) was apparent by 6/6/22 starting at 12.5 meters and expanded to shallower depths into late summer, reaching its shallowest depth at 7.5 meters by 8/31/22 (Appendix A, Table A2). Mixing of the water column following the breakdown of thermal stratification allowed well oxygenated surface waters to replenish poorly oxygenated bottom waters down to 12 meters depth by 10/7/22. Anoxia at 7.5-13 meters depth indicates the possibility of internal loading in Lake Kanasatka, as confirmed by the steady increase in hypolimnetic total phosphorus concentration at 13 meters depth throughout the season, reaching a peak of 201.3 µg/L on 9/21/22 (Figure 3). Historic dissolved oxygen and temperature profiles show that the extent of anoxia in Lake Kanasatka may be worsening, extending historically from 8.5-13 meters from 1977-2015 at 1-Deep to 7.5-13 meters from 2021-22 at 1-Deep. The possible increased prevalence of anoxia affecting bottom areas of the lake that are 7.5 meters or deeper represents a significant shift in the potential for phosphorus release from sediment because the surface area change from 8.5+meters to 7.5+meters is large (Figure 4).

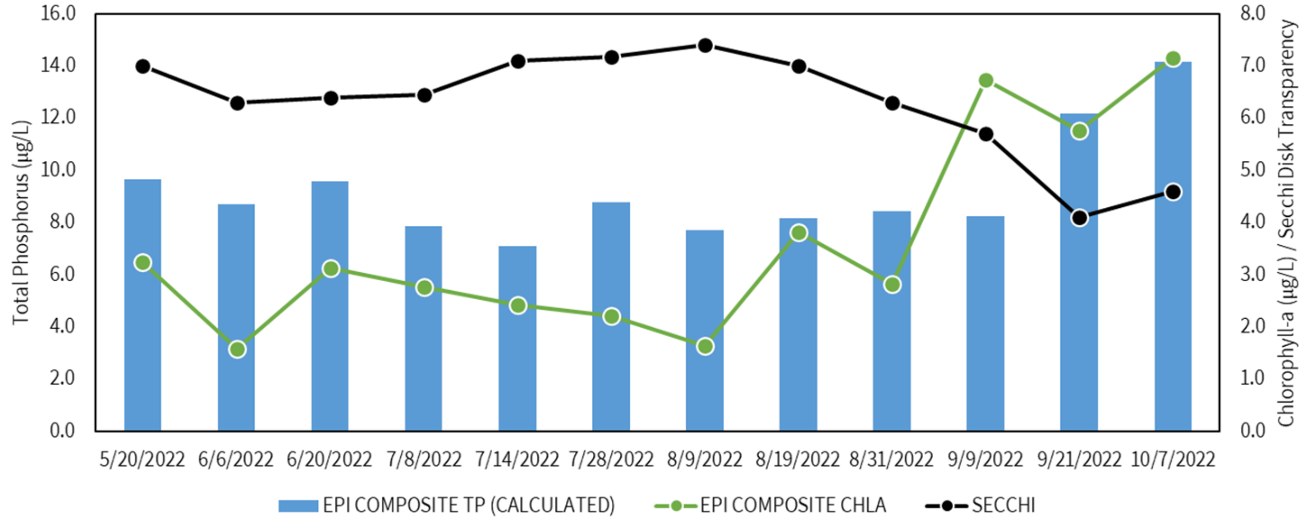

Figure 2. Epilimnetic total phosphorus and chlorophyll-a concentrations and Secchi Disk Transparency readings for each 2022 sample date at the deep spot (1 Deep) of Lake Kanasatka. Epilimnetic total phosphorus is calculated as the volume-weighted average epilimnetic (for 1-, 3-, 5-, and 7-meter grabs) total phosphorus concentration.

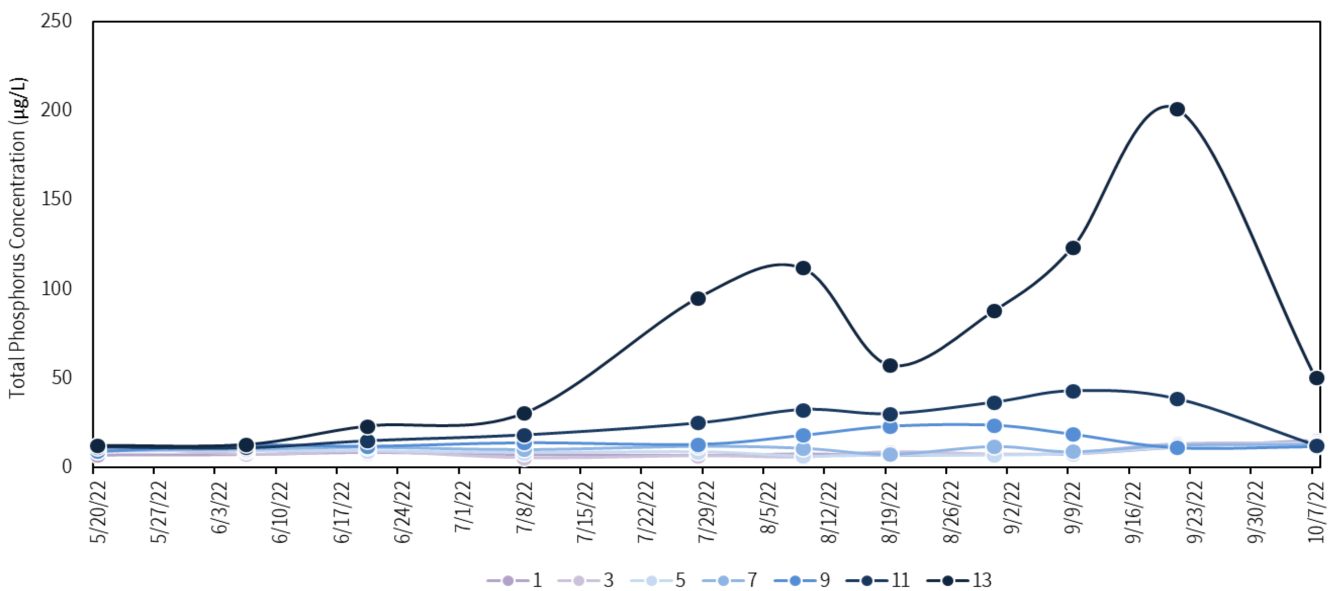

Figure 3. Total phosphorus concentration by depth (meters) at the deep spot (1 Deep) of Lake Kanasatka for each 2022 sample date.

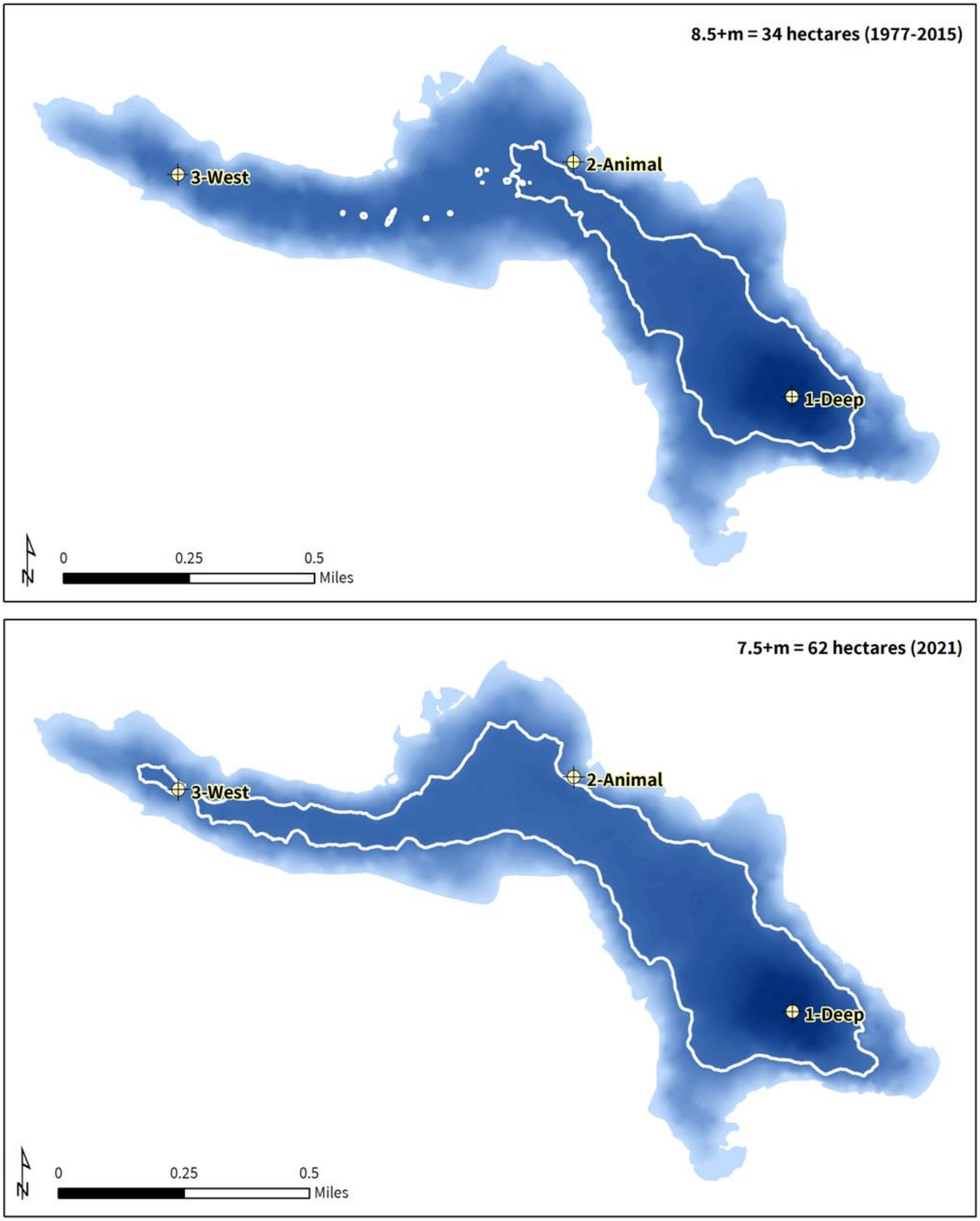

Figure 4. Bathymetric map depicting the increased extent of anoxia in Lake Kanasatka from 34 hectares at 8.5+meters for dissolved oxygen profiles collected from 1977-2015 to 62 hectares at 7.5+meters for dissolved oxygen profiles collected in 2021 and 2022.

Aside from an expanding anoxic zone in Lake Kanasatka, another factor to consider for explaining the sudden bloom issues is changes in the lake's food web, notably seasonal patterns in zooplankton biomass. For Lake Kanasatka in 2022, crashes in the herbivorous zooplankton populations (< 50 µg/L) generally coincided with the two major cyanobacteria blooms in July and August (Figure 5). Small fish such as black crappie, white and yellow perch, and pumpkinseed (common sunfish) present in Lake Kanasatka, as well as the larval and/or juvenile stages of piscivorous fish species, eat zooplankton as one of their food sources. The predatory zooplankter, Chaoborus, also eats small-boded zooplankton like Cladocera. Depending on the life cycle stage and season, grazing of zooplankton by fish or predatory zooplankton can be intense, and without sufficient zooplankters grazing phytoplankton, cyanobacteria can proliferate. *Daphnia* are among the most efficient grazers of phytoplankton but are generally present in small, though not insignificant, amounts in Lake Kanasatka, suggesting possible over predation by small fish or predatory zooplankton at certain times of the year. The herbivorous zooplankton population rebounded in October but was unhelpful in reducing the extent and severity of the bloom because the mixing of bottom waters to the surface following the breakdown of thermal stratification increased total phosphorus concentrations at the surface to above 10 µg/L, which further fueled the bloom.

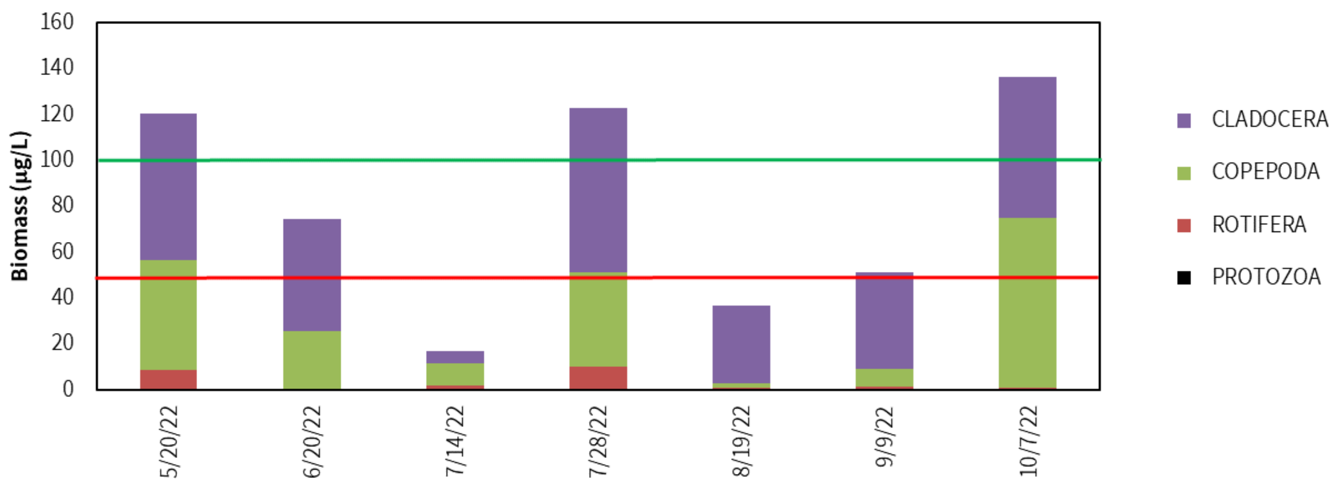

Figure 5. Estimated biomass of generally herbivorous zooplankton for each 2022 sample date collected at the deep spot (1 Deep) of Lake Kanasatka. The green horizontal line marks 100 µg/L above which is a general indication of sufficient grazing capacity to keep cyanobacteria and other algae from blooming. The red horizontal line marks 50 µg/L below which is a general indication of insufficient grazing capacity to keep cyanobacteria and other algae from blooming.

Phosphorus Source Loads

As part of the development of the Lake Kanasatka Watershed-Based Management Plan, a Lake Loading Response Model (LLRM) was used to estimate water and phosphorus source loads and predict in-lake water quality for Lake Kanasatka. Water and phosphorus loads (in the form of mass and concentration) are traced from various sources in the watershed through tributary basins and into the lake. The model incorporates data about watershed and sub-watershed boundaries, land cover, point sources (if applicable), septic systems, waterfowl, rainfall, volume and surface area, and internal phosphorus loading. These data are combined with coefficients, attenuation factors, and equations from scientific literature on lakes, rivers, and nutrient cycles to generate annual average predictions[2] of total phosphorus, chlorophyll-a, Secchi disk transparency, and algal bloom probability. The model can be used to identify current and future pollutant sources, estimate pollutant limits and water quality goals, and guide watershed improvement projects. A complete detailing of the methodology employed for the Lake Kanasatka LLRM is provided in the *Lake Kanasatka Lake Loading Response Model Report* (FBE, 2022a), with updates described in FBE (2023) based on 2022 data[3]. A comparison of results from the original and updated models is provided in Table 2 and Figure 6.

Per the updated (2022) model, watershed runoff combined with baseflow (61%) is the largest phosphorus loading contribution across all sources to Lake Kanasatka, followed by internal loading at 20% and shorefront septic systems[4] at 10% (Table 2; Figure 6). Atmospheric deposition (6%) and waterfowl (3%) were relatively minor sources. Development in the watershed is most concentrated around the shoreline where septic systems or holding tanks are located within a short distance to the water, leaving little horizontal (and sometimes vertical) space for proper filtration of wastewater effluent. Improper maintenance or siting of these systems can cause failures, which leach untreated, nutrient-rich wastewater effluent to the lake.

As the second most significant source of phosphorus to the lake, internal phosphorus loading is legacy external phosphorus loading that recycles back into the water column and potentially fuels cyanobacteria growth. There are several modes by which phosphorus is recycled back into the water column[5], with the release of iron bound phosphorus in surficial sediments during anoxic periods being typically the most substantial, particularly in deep stratified lakes such as Lake Kanasatka. As decomposition in the sediment increases with rising temperatures, oxygen demand rapidly depletes available oxygen, then other electron acceptors such as nitrate, manganese oxides, and finally iron oxides, which releases iron bound phosphorus. While oxygen can only decline to a concentration of zero, redox potential can continue to decline below zero, increasing the rate of phosphorus release even after oxygen is depleted.

---

[2] The model cannot simulate short-term weather or loading events.

[3] FBE completed an update to the 12/23/21 LLRM for Lake Kanasatka. Specifically, FBE changed the 10-year (2012-2021) precipitation average to a 3-year (2020-2022) precipitation average, which lowered the input value from 1.24 to 1.09 meters. FBE also reassessed the internal phosphorus load estimate based on the more robust 2022 data collected. To calculate the internal phosphorus load, the volume-weighted average epilimnetic (for 1-, 3-, and 5-meter grabs) total phosphorus concentration was subtracted from the total phosphorus concentration at subsequent depths (7, 9, 11, and 13 meters) impacted by anoxia. Positive values were summed for the total internal phosphorus load on each sample date. The maximum internal phosphorus load occurred on 8/31/22 at 55.5 kg, which was used as the annual internal load estimate in the model update and likely represents a more accurate estimation of internal phosphorus load compared to the original estimate of 70.4 kg/yr. The observed in-lake total phosphorus concentration for calibration was adjusted to the average median monthly concentration for 2021-2022 (2020 was excluded with only one data point), lowering from the original calibration value of 9.0 µg/L to 8.6 µg/L in the model update. Adjusting for a 20% increase to represent an annual average in-lake total phosphorus concentration, the new calibration value was set at 10.3 µg/L, which compares well with an early spring (5/20/22) whole column mixed average of 10.4 µg/L. Reckhow General (1977) continues to be the best predictor of Lake Kanasatka at 10.4 µg/L.

[4] Note that 1) the estimate for the septic system load is only for those systems directly along the shoreline and potentially short-circuiting minimally treated effluent to the lake; and 2) the load from septic systems throughout the rest of the watershed is inherent to the coefficients used to generate the watershed load.

[5] Other modes include plant cell uptake from sediments and subsequent leakage, organic matter decay, bioturbation from bottom feeding fish or other biota, and mechanical mixing from wind or boat wake action.

Table 2. Total phosphorus (TP) and water loading summary by source for Lake Kanasatka, comparing the original 2021 model with the updated 2022 model.

SOURCE	ORIGINAL (2021)			UPDATED (2022)		
	TP (KG/YR)	%	WATER (CU.M/YR)	TP (KG/YR)	%	WATER (CU.M/YR)
ATMOSPHERIC	15.7	5%	1,041,494	15.7	6%	820,503
INTERNAL	70.4	24%	0	55.5	20%	0
WATERFOWL	8.6	3%	0	8.6	3%	0
SEPTIC SYSTEM	27.7	10%	20,540	27.7	10%	20,540
WATERSHED LOAD	170.2	58%	8,607,904	170.2	61%	7,536,853
TOTAL LOAD TO LAKE	**292.5**	**100%**	**9,669,939**	**277.6**	**100%**	**8,377,897**

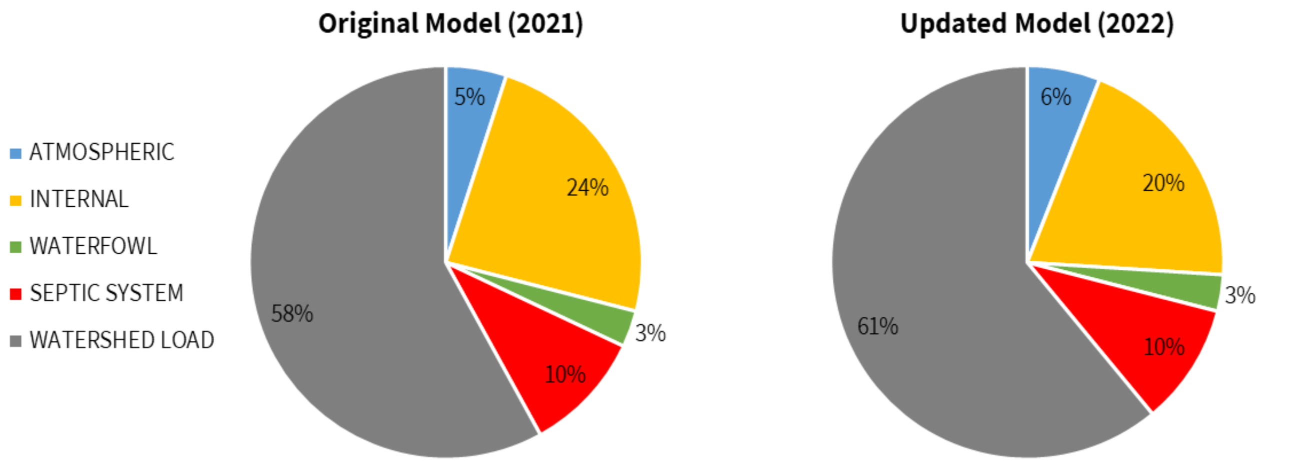

Figure 6. Total phosphorus (%) loading summary by source for Lake Kanasatka, comparing the original 2021 model (LEFT) with the updated 2022 model (RIGHT).

Planning & Implementation History

In response to the onset of these blooms, LKWA hired environmental consulting firm FB Environmental Associates (FBE) to develop an a-i watershed-based management plan for Lake Kanasatka, which was finalized in August 2022. Using water quality data collected by LKWA and UNH LLMP since 1983, sources of phosphorus in the watershed impacting the lake's water quality were identified and quantified and included stormwater runoff from developed areas, shoreline erosion, erosion from construction activities or other disturbed ground particularly along roads, excessive fertilizer application, failed or improperly functioning septic systems, unmitigated agricultural activities, and pet, livestock, and wildlife waste. Twenty-two (22) problem sites were identified in the watershed during a field survey conducted by FBE. The main issues identified were unpaved road and ditch erosion, buffer clearing, and untreated stormwater runoff. Additionally, 121 shorefront properties (66% of the total 182 shorefront properties) were identified as having some impact to water quality due to evidence of erosion and lack of vegetated buffer. Internal phosphorus loading was also estimated to contribute significantly to the total phosphorus load.

Following FBE's recommendations for additional data collection, LKWA in partnership with UNH LLMP collected additional lake sampling data in 2022. FBE used the data to assess the water quality condition of Lake Kanasatka in 2022 and refine the internal load estimate as part of an updated lake model for Lake Kanasatka (FBE, 2023). With the higher resolution total phosphorus data collected throughout the water column at the deep spots, FBE determined that the internal phosphorus load is 20%.

The goal of the Lake Kanasatka Watershed-Based Management Plan is to improve the water quality of Lake Kanasatka such that it meets state water quality standards for the protection of Aquatic Life Integrity and substantially reduces the likelihood of harmful cyanobacteria blooms in the lake. This goal will be achieved by reducing the phosphorus loading to Lake Kanasatka by 48 kg/yr (revised in 2023) to meet an annual average in-lake total phosphorus concentration of 7.2 ppb.

Addressing identified opportunities for reduction of external sources of phosphorus load was estimated at 43 kg/yr, meeting 90% of the needed reductions to achieve the goal of 48 kg/yr of phosphorus reduced. This would require remediating 22 watershed survey sites (11 kg/yr), treating 121 or 66% of shorefront properties (20 kg/yr), and upgrading 115 shorefront septic systems (12 kg/yr). Because it would be unrealistic to achieve this work within a reasonable timeframe and because more reduction in phosphorus load would still be needed, reducing the internal phosphorus load to Lake Kanasatka is also needed to achieve the goal. It is also important to consider the time of year when internal loading and the risk of cyanobacteria blooms are highest and the portion of the total load coming from internal load rises to an estimated 46% in August. Thus, successful restoration of Lake Kanasatka will require addressing both internal and external phosphorus loads.

LKWA requested an in-person meeting on 5/22/23 with NHDES and other critical partners to discuss the lake’s cyanobacteria issues and come to a consensus on the best management options. NHDES concluded that there was enough existing data to show that an in-lake treatment is needed for Lake Kanasatka and that the modeling estimates were sufficient as is and could be updated as remediation work continues. NHDES also stressed that successful restoration of Lake Kanasatka will require addressing both internal and external phosphorus loads and that LKWA will need to work with NHDES to meet a particular target for external load reduction to proceed with an in-lake treatment. Following the meeting, NHDES shared preliminary documentation that determined an external phosphorus load reduction of 10 kg/yr will be required to proceed with permitting an in-lake treatment.

LKWA has since met the goal of reducing 10 kg/yr of external phosphorus load to the lake (Table 3) in support of an in-lake treatment that would achieve a conservative reduction of 44 kg/yr of phosphorus. Thus, a total of 54 kg/yr of phosphorus (113% of the goal) will be achieved to fully restore Lake Kanasatka following the spring 2024 alum treatment.

LKWA has worked extensively this year to address priority sites identified in the WMP and has been actively pursuing funding for additional implementation work. LKWA enlisted the help of 53 volunteers to complete projects such as installing drainage ditches and water razors and stabilizing pathways around the watershed in 2023. Two volunteers donated considerable time using their large tractor/loader/backhoe and small tractor/loader. One volunteer completed 21 consultations for using rubber razors to divert runoff which resulted in 16 installed razors, not including five that were installed on Camp Quinebarge property. Another volunteer completed 18 consultations with property owners and completed 12 projects. Sixteen (16) shorefront properties around Lake Kanasatka have become LakeSmart certified since 2019, with six awarded in 2022 and seven awarded in 2023. At the request of LKWA, the Moultonborough Public Works Director completed grading of Glidden Road and added stone swales to Red Hill Rd in 2023. Due to persistent communication from LKWA, the NHDOT and NHDES Bureau of Dams are in progress to renovate the boat launch/dam area and have ceased dumping/plowing snow at the dam. NHDOT also completed improvements to Route 25 that has reduced sediment loading to the lake. Ten (10) septic system upgrades were documented around the lake since 2021, with two more planned.

LKWA contracted FBE to calculate the phosphorus load reductions from implemented shoreline and watershed best management practices (BMPs). On 9/29/2023 and 10/2/2023, FBE technical staff visited 12 shoreline properties and re-evaluated nine watershed survey sites. Documentation of both shoreline and watershed survey sites included describing the past problems, documenting improvements made, logging the site's coordinates, and taking photographs. Table 3 summarizes the improvements made and pollutant load reduction calculations. LKWA will continue to track watershed improvements moving forward.

LKWA also successfully applied for 319 Watershed Assistance Grant program funding to remediate two BMP sites along Burton Rd (1-17, 1-18) as identified during the watershed survey as part of the Watershed-Based Management Plan.

LKWA is also promoting a septic system ordinance with the Town of Moultonborough, similar to ordinances passed in other towns across New Hampshire, notably in Meredith, Sunapee, Windham, New Durham, and Deering. This ordinance requires all septic systems within 250 feet of the lake reference line to pump their septic system within two years; have their septic system evaluated and certified within two years; and brought into compliance within three years. Pumping, evaluating, and complying would be required at least every five years. Every septic system replacement or upgrade could achieve 0.1 kg/yr in phosphorus load reduction to the lake. If this ordinance is passed and enforced, every septic system replacement or upgrade will contribute to the extended longevity of the in-lake treatment.

Table 3. Site ID, location, type of each implemented BMP, and associated load reductions within the Lake Kanasatka watershed.

SITE ID / Map-Lot#	LOCATION	LakeSmart Certification	BMP TYPE	LOAD REDUCTION		
				TSS (metric tons/yr)	TP (kg/yr)	TN (kg/yr)
COMPLETED SITES						
136-13	10 Foster Drive	Yes	Shoreline	0.03	0.08	0.44
112-15	119 Kanasatka Road	No	Shoreline	0.15	0.33	1.92
112-22	155 Kanasatka Road	No	Shoreline	0.17	0.39	0.36
136-11	18 Foster Drive	In progress	Shoreline	0.16	0.34	1.57
137-18	38 Avon Shores Road	Yes	Shoreline	1.08	1.10	8.72
142-40	4 Jacks Road	Yes	Shoreline	0.26	0.57	0.43
137-14	48 Avon Shores Road	Yes	Shoreline	0.16	0.33	2.09
113-24	62 Vonhurst Road	Yes	Shoreline	0.17	0.36	0.28
113-4	73 Bishop Shore Road	In progress	Shoreline	0.10	0.22	1.00
136-10	77 Ames Road	Yes	Shoreline	0.21	0.45	2.18
112-49	89 Coe Point Road	Yes	Shoreline	0.11	0.26	0.24
137-28a	Birchwood Association (end of VonHurst Rd)	No	Shoreline	0.63	1.37	1.23
1-03	Shady Lane Construction Site (now Maple Lane)	-	WMP BMP Site	0.71	1.64	7.11
1-12	Red Hill Road stream Crossing	-	WMP BMP Site	0.09	0.15	0.43
1-13	Culvert under Deer Crossing	-	WMP BMP Site	0.10	0.19	0.65
1-16	Rite of Way off Ames Road	-	WMP BMP Site	0.36	0.64	2.12
1-19A	Camp Quinebarge Beach	In Progress	Additional Site	0.17	0.33	0.20
1-19B	Camp Quinebarge Paths	In Progress	WMP BMP Site	0.45	0.97	0.69
1-20	Common Beach off Brook Road to Wakondah Pond	-	WMP BMP Site	0.00	0.06	0.05
1-22	Sandy Cove Road	-	WMP BMP Site	0.74	1.50	4.80
1-11	Bean Road Shoulder Along Pond	-	WMP BMP Site	0.00	0.00	0.00
112-15	119 Kanasatka Road (Fall 2021)	No	Septic System Upgrade Complete	-	0.10	-
107-15	20 Deer Crossing (Summer 2021)	No	Septic System Upgrade Complete	-	0.10	-
114-17	33 Bishop Shore Rd (Oct 2023)	No	Septic System Upgrade Complete	-	0.10	-
142-75	7 Wylie Way (June 2022)	No	Septic System Upgrade Complete	-	0.10	-
114-6	109 Red Hill Road (2021)	No	Septic System Upgrade Complete	-	0.10	-
112-13	109 Kanasatka Road (2021)	No	Septic System Upgrade Complete	-	0.10	-
114-18	35 Bishop Shore Road (2023)	No	Septic System Upgrade Complete	-	0.10	-
136-13	10 Foster Drive (2021)	Yes	Septic System Upgrade Complete	-	0.10	-
142-40	4 Jacks Road (2021)	Yes	Septic System Upgrade Complete	-	0.10	-
112-7	28 Westwood Shores (2021)	Yes	Septic System Upgrade Complete	-	0.10	-
			Total Load Reduction	**5.86**	**12.30**	**36.52**
TO BE COMPLETED SITES						
1-05	Boat Ramp	-	WMP BMP Site - Planned by State	1.07	1.08	7.73
1-17	Burton Rd	-	WMP BMP Site - Planned for 319 Grant	0.31	0.37	0.88
1-18	95 Burton Rd, two residential properties	-	WMP BMP Site - Planned for 319 Grant	0.13	0.32	0.77
113-16	83 Coe Point Road	No	Septic System Upgrade Planned	-	0.10	-
112-53	111 Coe Point Rd (Spring 2024)	No	Septic System Upgrade Scheduled	-	0.10	-
			Potential Additional Load Reduction	**1.50**	**1.97**	**9.37**

SEDIMENT ANALYSIS

On July 20, 2021 and October 17, 2023, NHDES collected 10 lake bottom sediment cores (top 10 cm or 4 in) from a gradient of water depths around the lake (Figure 7) to (1) characterize the spatial variability in sediment properties, (2) assess the risk of internal phosphorus loading, (3) determine the mass of mobile phosphorus available for release under anoxic conditions, and (4) determine the feasibility of a sediment phosphorus inactivation option to reduce the internal phosphorus load in Lake Kanasatka. Refer to the Alternatives Analysis section for further discussion of in-lake treatment feasibility across a range of options.

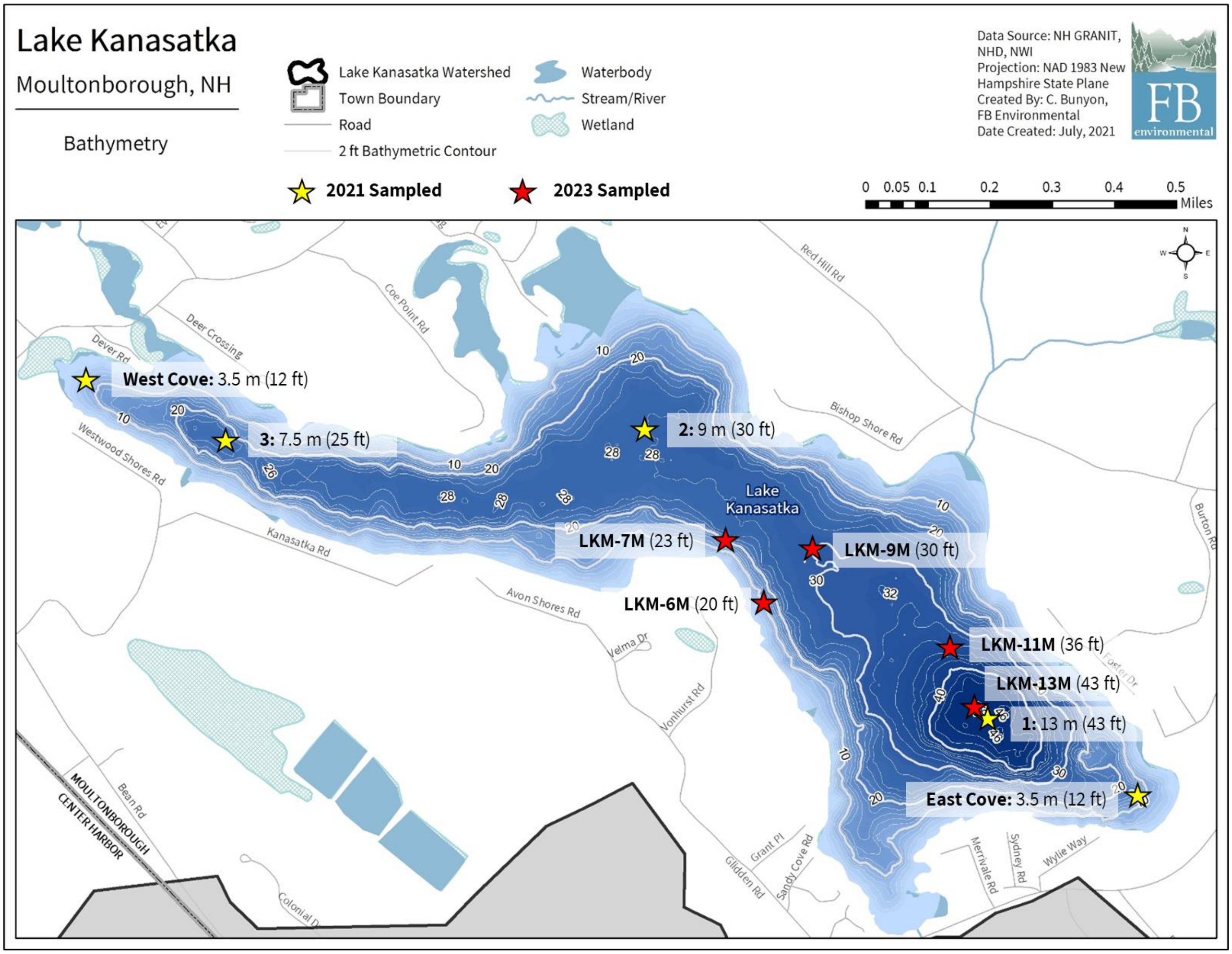

Figure 7. Sediment sampling locations at Lake Kanasatka. Sampling locations were selected at a variety of depths and at the deepest spots in the lake.

Methodology

For each intact core retrieved from the lake bottom using a gravity sediment coring device, excess water was siphoned off and gloves were worn when bagging the sample to prevent contamination. Sediment cores were deposited in labeled zipped locked bags, double-bagged, and placed in a cooler for overnight shipping to the University of Wisconsin-Stout Center for Limnological Research and Rehabilitation Laboratory (U-Wisconsin) for analysis of moisture content, wet and dry bulk density, loss on ignition (LOI) or organic content, total phosphorus, total iron, total aluminum, and biologically labile phosphorus by sequential lab extractions (Psenner and Puckso, 1988).

Sediment core collected by NHDES at LKM-7M on October 17, 2023. © NHDES

Phosphorus fractions analyzed included loosely bound phosphorus, iron bound phosphorus, labile organic phosphorus, and aluminum bound phosphorus and respectively represent the increasing degree in which phosphorus is bound in the sediment. Loosely bound phosphorus is the most readily available fraction for uptake by biota. Iron bound phosphorus is phosphorus bound to iron which can be released under low oxygen conditions. Labile organic phosphorus is phosphorus bound to organic matter that is slowly released during microbial decomposition and is generally less available than loosely and iron bound phosphorus fractions but can still be a significant contributor to the internal phosphorus load. Aluminum bound phosphorus is phosphorus bound to aluminum which is generally considered permanently retained within sediments except under high pH conditions. The remaining fraction of phosphorus is considered “refractory,” including calcium bound phosphorus, and is permanently retained within sediments.

Loosely bound, iron bound, and labile organic phosphorus fractions are released into the water column under varying conditions and by varying rates throughout the year, but most prominently in late summer when the anoxic extent is greatest. The phosphorus released to the hypolimnion can be transported to the epilimnion through several mechanisms, such as diffusion, mixing, and a deepening thermocline. Once in or near the epilimnion, the phosphorus can be readily taken up by phytoplankton.

Note: The phosphorus fractionation procedure can inject some uncertainty in our assumptions and calculations. Therefore, it is helpful to understand the limitations of the procedure and subsequent results. In general, the procedure adds stronger reagents with each step to extract more strongly bound phosphorus in the sediment. Loosely adsorbed and pore water phosphorus (i.e., “loosely bound phosphorus” as reported by U-Wisconsin) is extracted in the first step using ammonium chloride. In the next step, the redox-sensitive fraction of phosphorus that is bound to iron and manganese (i.e., “iron bound phosphorus” as reported by U-Wisconsin) is extracted using sodium dithionite in a sodium bicarbonate buffer (a.k.a, bicarbonate-dithionate extraction, or BD-P). In the next step, sodium hydroxide is used to extract the remaining nonreducible iron oxides and aluminum oxides (i.e., “aluminum bound phosphorus” as reported by U-Wisconsin). The sample is then digested, and the organic phosphorus fraction is derived as a calculated difference (i.e., “labile organic phosphorus” as reported by U-Wisconsin). The remaining fraction of the total phosphorus in sediment is considered refractory and includes calcium and other inorganic bound phosphorus (which can be extracted with hydrochloric acid) and immobile organic phosphorus. The steps in this chemical extraction procedure are imperfect and can over or underestimate phosphorus pools if one target pool is not completely extracted in a step (and shows up in the next step) or if the addition of a chemical solution causes pool redistribution, whereby iron and aluminum co-precipitate with phosphorus and interfere with the accuracy of phosphorus fraction estimates. In addition, lake sediments show high spatial heterogeneity (Pilgrim et al., 2007) and can vary temporally (Rydin and Brunberg, 1998), making the sediment samples themselves variable and lending uncertainty to the analysis.

Sediment Characterization

Results show that loosely bound phosphorus is low at all depths in the lake (Table 4). Iron and aluminum bound phosphorus both increase with progressively deeper areas of the lake, which is expected given that sediments tend to migrate to deeper parts of the lake over time. Labile organic phosphorus is also higher in deeper areas of the lake, indicating that the labile organic fraction of phosphorus (in addition to the iron bound phosphorus) could be a significant source of phosphorus release to the hypolimnion.

Overall, there is a marked difference in the sediment properties of deeper areas of the lake (7.5 m and deeper) compared to shallower areas of the lake (<7.5 m) (Figure 8). Shallower areas of the lake show significantly less total phosphorus mass and thus less mobile phosphorus mass in the sediments. Deeper areas of the lake have higher water content (less percent solids) and higher organic content compared to shallower areas of the lake (Figure 9). Deeper areas of the lake also have higher concentrations of total phosphorus, aluminum, and iron compared to shallower areas of the lake (Figure 10).

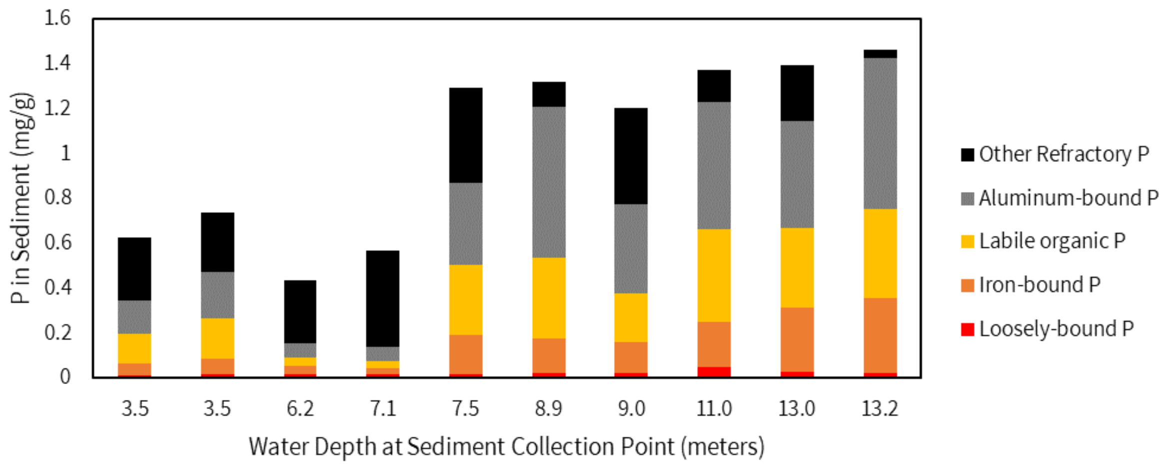

Figure 8. Phosphorus fractions in sediment cores (representing top 10 cm or 4 in) at various water depths across Lake Kanasatka. Refer to Table 4 for data and Figure 7 for locations.

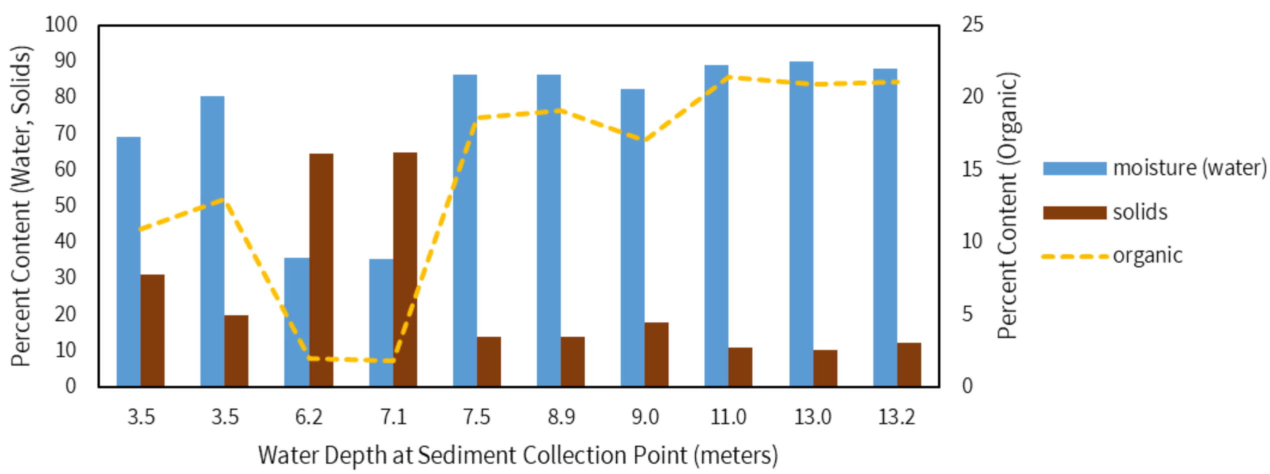

Figure 9. Water, solids, and organic matter content (percent, %) in sediment cores (representing top 10 cm or 4 in) at various water depths across Lake Kanasatka. Refer to Table 4 for data and Figure 7 for locations.

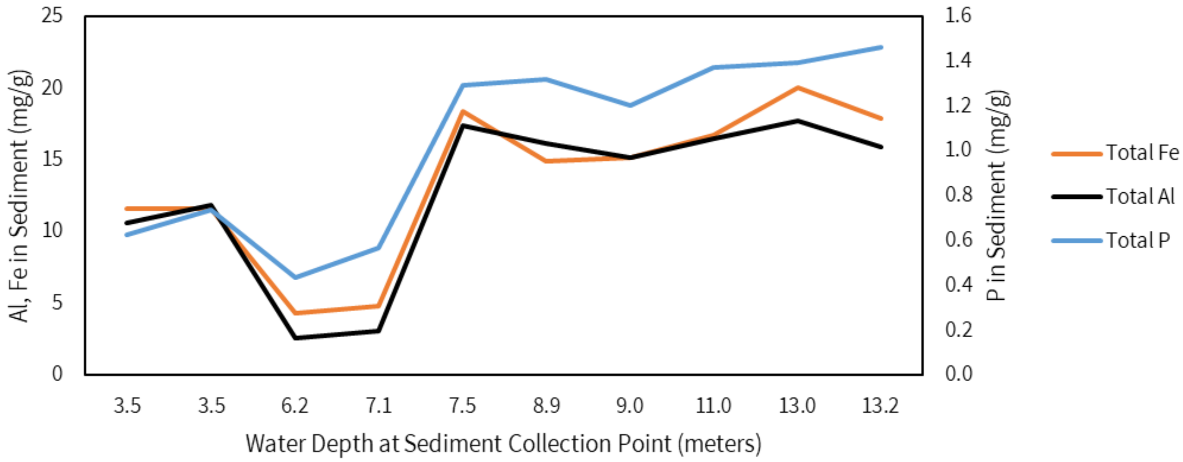

Figure 10. Total phosphorus, aluminum, and iron concentration (mg/g) in sediment cores (representing top 4 in or 10 cm) at various water depths across Lake Kanasatka. Refer to Table 4 for data and Figure 7 for locations.

Internal Loading Risk

A high ratio of aluminum to iron (Al:Fe) and aluminum to phosphorus (Al:P) means that there is enough aluminum to permanently bind settled phosphorus, keeping the internal load in the lake low. Typically, an Al:Fe ratio of 3:1 or greater indicates that aluminum is present in enough abundance relative to iron that phosphorus is more likely to permanently bind to aluminum in the sediments (Norton et al., 2008). Additionally, an Al:P ratio of 25:1 or greater indicates that there is enough aluminum to bind with available phosphorus (Norton et al., 2008). Results show that Lake Kanasatka is vulnerable to internal loading due to Al:Fe ratios less than 3 and Al:P ratios less than 25 for all sampled sites (shallow and deep areas of the lake) (Table 4).

Mobile Phosphorus Mass Available

Mobile phosphorus in sediments is the sum of loosely bound, iron bound, and labile organic phosphorus, with loosely bound and iron bound being the most readily available fractions under anoxic conditions and labile organic phosphorus being available following decay over longer time periods (estimated at a rate of 5-10% per year). The average sediment concentration of loosely bound and iron bound phosphorus in deeper areas of the lake (>7.5 m) is 0.240 mg/g (Table 4). The average sediment concentration of all three fractions in deeper areas of the lake is 0.583 mg/g. Loosely bound and iron bound phosphorus typically drive internal phosphorus loading in lakes, but labile organic phosphorus can also play a significant role. It is therefore advantageous to consider treating a portion of the labile organic phosphorus fraction in addition to the loosely bound and iron bound phosphorus fractions.

As an alternate check on the internal phosphorus loading estimate from the prior modeling effort under the watershed-based management plan for Lake Kanasatka, we can assume that 10% of the mobile phosphorus mass in sediment is released and transported to the epilimnion in any given year for stratified lakes. Using the loosely bound and iron bound phosphorus fractions, with concentrations converted to mass based on percent solids, bulk density, and volume, we estimate an internal phosphorus load of 67 kg/yr based on the area-weighted average for

7.5 m and deeper and 57 kg/yr based on the anoxic time-weighted average[6] for 7.5 and deeper. Both estimates compare well with the internal phosphorus load calculated for the model at 55 kg/yr, which was based on observed 2022 phosphorus data in the hypolimnion. Thus, the sediment-based internal load estimates are likely within the range of observed, year-to-year variability. It also indicates that the labile organic phosphorus fraction may not be contributing much to the internal phosphorus load in Lake Kanasatka at this time, despite one study identifying low Fe:P ratios (<10), such as observed for Lake Kanasatka, as indicative of labile organic phosphorus decay being an important contributor to internal phosphorus load (Søndergaard et al., 2003). The sediment-based internal load estimates could be overestimates given the likelihood that the entire top 10 cm or 4 in of sediment does not contribute equally to the internal phosphorus load and that the labile organic phosphorus fraction contributes some amount of phosphorus to the hypolimnion each year.

Feasibility of Sediment Phosphorus Inactivation

Based on the analysis presented in this report thus far, we have concluded that sediment phosphorus inactivation is a feasible option for Lake Kanasatka for the following reasons:

1. Internal loading risk is high. Sediment data indicate low Al:Fe and Al:P ratios, indicating a high potential for phosphorus release from sediment.
2. Mobile phosphorus mass availability is high. Sediment data indicate a large amount of mobile phosphorus mass in sediment is available for release.
3. Anoxic extent is large and expanding. With the observed increasing extent of anoxia in the lake compounded by longer, warmer, and drier summers, it is likely that cyanobacteria blooms will continue and possibly increase in severity over time in Lake Kanasatka if the total phosphorus load to the lake is left unchecked.
4. Internal phosphorus load is significant. The internal load is estimated to be 20% of the total phosphorus load to the lake. When considering the time of year when internal phosphorus loading and the risk of cyanobacteria blooms are highest, in this case August, the internal phosphorus load portion of the total load increases to an estimated 46%. The cyanobacteria blooms that Lake Kanasatka experiences are whole lake issues fed by the internal phosphorus load during thermal stratification when waters are warm and calm with minimal mixing.

Work should continue to focus on reducing the watershed and septic system loads as together they contribute the most phosphorus to the lake; however, cyanobacteria blooms in Lake Kanasatka will likely persist in the future without a substantial reduction in the internal phosphorus load, regardless of any external phosphorus load reduction.

[6] Based on 2022 dissolved oxygen profiles, anoxic conditions (< 2 mg/L dissolved oxygen) were present for 150, 90, 60, and 10 days for depths 13 m and deeper, 11-13 m, 9-11 m, and 7.5-9 m, respectively. We assumed that the full 10% of phosphorus mass release from sediment could be realized for 13 m and deeper and the other depths would experience less than 10% phosphorus mass release based on the fraction of time spent under anoxia out of the 150 days possible.

Table 4. Sediment core sample results ordered from shallowest to deepest water depth collected. Data were collected by NHDES and analyzed by the University of Wisconsin-Stout Center for Limnological Research and Rehabilitation. Red indicates conditions favorable for release of phosphorus under anoxic conditions (Al:Fe <3, Al:P <25). P=Phosphorus. Al=Aluminum. Fe=Iron. Refer to Figure 7 for locations.

Date	Station Name	Depth	Depth	Moisture content	LOI	Wet bulk density	Dry bulk density	Loosely bound P	Iron bound P	Labile organic P	Aluminum bound P	Other Refractory P	Total P	Total Fe	Total Al	% Solids	Al:Fe	Al:P
	Units	ft	m	(%)	(%)	(g/cm³)	(g/cm³)	(mg/g)	(mg/g)	(mg/g)	(mg/g)	(mg/g)	(mg/g)	(mg/g)	(mg/g)	%	<3	<25
7/20/2021	East Cove	11.5	3.5	69.0	10.9	1.204	0.381	0.012	0.053	0.130	0.149	0.281	0.625	11.6	10.6	31.0	1.9	19.5
7/20/2021	West Cove	11.5	3.5	80.2	13.0	1.119	0.225	0.016	0.070	0.179	0.208	0.261	0.734	11.6	11.8	19.8	2.1	18.5
10/17/2023	LKM-6M	20.4	6.2	35.6	1.9	1.636	1.073	0.015	0.040	0.036	0.063	0.280	0.434	4.3	2.6	64.4	1.3	6.9
10/17/2023	LKM-7M	23.4	7.1	35.2	1.8	1.643	1.082	0.014	0.030	0.028	0.068	0.424	0.564	4.8	3.1	64.8	1.3	6.3
7/20/2021	3	24.6	7.5	86.3	18.6	1.074	0.150	0.018	0.172	0.312	0.369	0.424	1.295	18.4	17.4	13.7	2.0	15.4
10/17/2023	LKM-9M	29.2	8.9	86.3	19.1	1.073	0.149	0.022	0.154	0.360	0.673	0.108	1.317	14.9	16.1	13.7	2.2	14.0
7/20/2021	2	29.5	9.0	82.3	17.0	1.099	0.198	0.022	0.139	0.217	0.394	0.430	1.202	15.1	15.1	17.7	2.1	14.4
10/17/2023	LKM-11M	36.1	11.0	89.0	21.4	1.056	0.117	0.049	0.199	0.412	0.569	0.142	1.371	16.7	16.5	11.0	2.0	13.8
7/20/2021	1	42.7	13.0	90.0	20.9	1.051	0.107	0.026	0.285	0.355	0.478	0.247	1.391	20.0	17.7	10.0	1.8	14.6
10/17/2023	LKM-13M	43.3	13.2	87.8	21.1	1.063	0.131	0.024	0.329	0.400	0.672	0.037	1.462	17.9	15.9	12.2	1.8	12.5

ALTERNATIVES ANALYSIS

Several management alternatives with varying levels of effectiveness, longevity, cost, risk, and effort exist to address cyanobacteria blooms. Management alternatives typically focus on controlling factors that influence cyanobacteria growth and abundance: namely, light and nutrients. Management techniques such as dyes, surface covers, and selective plantings seek to establish light limitation, while methods such as nutrient input reduction, circulation, hypolimnetic or sediment oxygenation, dilution and flushing, drawdown, dredging, phosphorus inactivation, selective plantings, and selective withdrawal are used to reduce nutrient availability, directly or indirectly. Other techniques aim to target cyanobacteria through food-web manipulation or disrupting cellular processes (e.g., stocking herbivorous fish, removing bottom-feeding fish, algaecides, sonication).

For evaluating applicability to Lake Kanasatka, strong preference was given to techniques that reduce phosphorus loading, particularly internal phosphorus loading, as the primary source of nutrition supporting cyanobacteria growth. Given this preference and consideration for Lake Kanasatka's unique characteristics, many of the alternatives were not applicable and warranted no further consideration (Table 5; Appendix B). For example, sediment removal via dredging (Alternative 5, Appendix B) is expensive and disruptive to aquatic communities and recreation on the lake and is not recommended given the lake's large size. As another example, flushing (Alternative 3, Appendix B) can be beneficial in knocking back the severity of blooms but likely not in their entirely and could induce mixing favorable to species such as *Planktothrix*. Flushing used in this way would also need to be carried out during a time of year when water levels are already low and recreational use is high. Finally, circulation and destratification (Alternative 2, Appendix B) would destabilize thermal layers that are important to fish, lower dissolved oxygen in shallow water, and mix hypolimnion phosphorus into the epilimnion, all of which would likely worsen cyanobacteria blooms in Lake Kanasatka.

Recommended management techniques with the greatest applicability for Lake Kanasatka include external phosphorus load reduction through nonpoint source controls and pollutant trapping and phosphorus inactivation in surficial sediments.

- Reduction of external phosphorus load through nonpoint source controls and pollutant trapping (Alternatives 1b and 1c, Appendix B) is the primary recommendation for sustainable restoration of Lake Kanasatka. The Lake Kanasatka Watershed-Based Management Plan identified numerous nonpoint source pollution sites to remediate with structural BMPs, as well as several non-structural BMPs to reduce future sources of phosphorus from the watershed. Reducing the external phosphorus load extends the longevity of alum treatments, as it has been shown that in-lake treatment options are less effective if the external phosphorus load remains high (Nürnberg, 2017; Preece et al., 2019).
- Phosphorus-binding compounds (Alternatives 12 and 14, Appendix B) such as aluminum sulfate are added to the lake to permanently bind with phosphorus, stripping it from the water column and hindering its release from bottom sediments once settled. An internal load reduction of ~80% can be expected with phosphorus inactivation (Welch and Cooke, 1999). This is a one-time treatment over a few days in spring that typically lasts more than 10-20 years, depending on the sedimentation rate of the waterbody and the effectiveness of external phosphorus load reduction efforts. This technique has proved successful in many lakes throughout the country and has been used recently in one New Hampshire lake (Nippo Lake in Barrington) and several Maine lakes (e.g., Long Pond in Parsonsfield, East Pond in Oakland, and Lake Auburn in Auburn).

Other management techniques with potential applicability for Lake Kanasatka include hypolimnetic aeration and oxygenation, algaecides, sediment oxidation, and enhanced grazing through food chain interactions (Table 5;

Appendix B).

- Hypolimnetic oxygenation and aeration (Alternative 10, Appendix B) can be extremely effective in managing blooms driven by internal phosphorus loading. Bottoms waters are oxygenated in the summer months to prevent anoxia. Without anoxia, most of the phosphorus would remain in the sediments. Oxygenating bottoms waters have the added benefit of improving suitable habitat for sensitive fish species seeking cooler, well oxygenated waters in the hot summer months. The major disadvantages are the high initial and ongoing costs and technical expertise needed.
- Sediment oxygenation (Alternative 13, Appendix B) also retains iron bound phosphorus in sediments, though the technique is not well vetted currently.
- Algaecides and other techniques to lyse cyanobacteria cells (Alternative 11, Appendix B) are a commonly applied strategy but do not confront the source of algal nutrition and would require repeated applications, thus other management options are preferred for long-term restoration of Lake Kanasatka.
- Enhanced grazing through food chain interactions (Alternative 16b, Appendix B) involves rebalancing the food web to increase the grazing zooplankton population that feed on cyanobacteria. This usually means stocking surface waters with piscivores (fish which eat smaller fish) to keep planktivores (fish which eat zooplankton) in check. Zooplankton data collected in 2022 for Lake Kanasatka showed a relatively healthy population without obvious evidence of overpredation. Cyanobacteria are generally less desirable to zooplankton as a food source; thus, food web manipulation may have minimal effect on cyanobacteria growth. Maintaining a balanced biological community in the lake also provides a buffer against cyanobacteria blooms and enhances uses such as fishing and wildlife viewing and is worthwhile as a supplemental in-lake technique.

Table 5. Range of options for control of cyanobacteria in lakes sorted by applicability to address current conditions in Lake Kanasatka (recommended options are shaded).

Options potentially applicable	Options deemed not applicable
• Nonpoint source control of phosphorus (watershed- based plan)	• Point source control of phosphorus
• Pollutant trapping (watershed-based plan)	• Circulation and destratification
• Hypolimnetic aeration or oxygenation	• Dilution and flushing
• Algaecides	• Drawdown
• Sediment oxidation	• Dry excavation of sediment after drawdown
• Phosphorus inactivation	• Wet excavation of sediment from shore
• Settling agents	• Hydraulic dredging
• Enhanced grazing through food chain interactions	• Light limiting dyes
	• Surface covers
	• Mechanical removal/treatment on shore
	• Selective withdrawal of water
	• Sonication
	• Iron-nanoparticles
	• Selective nutrient addition
	• Addition of herbivorous fish
	• Bottom feeding fish removal
	• Microbial competition
	• Addition of pathogens
	• Plantings of macrophytes for nutrient utilization
	• Plantings of macrophytes for shade
	• Addition of barley straw
	• Floating wetlands
	• Acidification

PROPOSED PROJECT

Based on the preceding assessments, the proposed project uses a phosphorus inactivation approach to bind phosphorus in surficial sediments through the application of aluminum as aluminum sulfate (alum). The alum treatment is expected to reduce the internal phosphorus loading to Lake Kanasatka by up to 90%, resulting in significantly improved water quality. Based on techniques developed in the 1970s and refined in the 1990s (Welch and Cooke, 1999; Rydin and Welch, 1998, 1999), alum treatments have been used successfully to reduce the internal phosphorus loading in lakes in New England for the last 30 years.

Calculations & Assumptions

The successful application of alum is based on a calculated dose and treatment area. The following inputs and assumptions were considered in determining the appropriate alum dose and treatment area for Lake Kanasatka:

- **The treatment area should encompass the area of sediment exposed to anoxia, defined as dissolved oxygen concentrations less than 2 mg/L.** Based on sediment data showing a distinct difference in sediment properties in deeper (>7.5 m) and shallower (<7.5 m) areas of the lake, with less mobile P available in shallower areas, and recent profile data showing anoxia extending to 7-7.5 m and deeper, we selected a treatment area of 7.5 m and deeper. While internal phosphorus loading may occur in shallower areas, it appears to be minor compared to the deeper areas.
- **The target sediment depth for inactivation was set at 10 cm.** Sediment cores of 10 cm were collected in the field in anticipation of this target sediment depth for dose calculations. Prior studies have shown that phosphorus within the upper 4 to 10 cm (up to possibly 20 cm) of sediment is able to mobilize and move up to the sediment-water interface where it can be released to the water column (Rydin and Welch, 1998; Welch and Cooke, 1999; Cooke et al., 2005; Welch et al., 2017).
- **Mobile phosphorus included loosely bound and iron bound phosphorus, with consideration for labile organic phosphorus.** See section on Mobile Phosphorus Mass Available. The loosely bound and iron bound phosphorus are substantial on their own. The labile organic phosphorus is also substantial. To stay within a reasonable and safe dose range for Lake Kanasatka, only the loosely bound and iron bound phosphorus were targeted for treatment, with consideration for labile organic phosphorus, as explained below.
- **The mobile phosphorus mass per square meter to be treated is based on volumetric estimates using sediment volume, density, and percent solids.** The dry weight of phosphorus mass in sediment is converted to a volumetric concentration based on the mass of phosphorus per volume of sediment sampled. This approach helps to improve the accuracy of dosage calculations.
- **The aluminum to phosphorus (Al:P) binding ratio was set at 20:1.** The Al:P binding ratio is essentially a multiplication factor to ensure there is an excess of aluminum as alum floc (without overtreating) to strip phosphorus out of the water column and bind with loosely bound and iron bound phosphorus in surficial sediment; the remaining unbound alum floc can bind with newly mobilized phosphorus as it moves upward from lower sediment depths, particularly from the labile organic fraction as it decays over time. The selection of an appropriate Al:P binding ratio first considers binding efficiency as a function of the mass of mobile phosphorus. The Al:P binding ratio varies inversely with the iron bound phosphorus concentration, meaning that more aluminum to phosphorus (i.e., a high Al:P binding ratio) is needed at low iron bound phosphorus concentrations in the sediment (James and Bischoff, 2015). The alum floc mixes within the top few inches of sediment and becomes dilute; thus, at low iron bound phosphorus concentrations, the alum floc will not come into frequent contact with iron bound phosphorus for binding and so will be less efficient at binding (and a high Al:P binding ratio is needed). Al:P binding ratios for

loosely bound and iron bound phosphorus generally range from 10 to 20 (James and Bischoff, 2015; Jensen et al., 2015; Reitzel et al., 2005; Rydin et al., 2000; Rydin and Welch, 1999; Kuster et al., 2020). In the case of Lake Kanasatka, the loosely bound and iron bound phosphorus concentration is high, suggesting that an Al:P binding ratio on the low end of the typical range (i.e., 10) will be sufficient for efficient binding of that mobile fraction. The selection of an appropriate Al:P binding ratio can also consider the labile organic phosphorus fraction as part of the mobile phosphorus pool to treat. When considering the labile organic phosphorus fraction for treatment, an Al:P binding ratio at the higher end of the range may be selected to help account for a portion of the labile organic fraction. Alternatively, a separate dose calculation can be performed for the labile organic fraction, using an Al:P binding ratio between 5 and 10, and added to the dose for loosely bound and iron bound phosphorus for a total treatment dose. While more recent alum treatments are incorporating the labile organic phosphorus fraction into dose calculations, it is important to understand that the higher dose applied today treats future phosphorus from the decay of the labile organic phosphorus fraction over time; however, the alum floc ages over time and becomes less effective at binding newly mobilized phosphorus. Therefore, treating 100% of the labile organic phosphorus fraction may be an overtreatment, particularly if sedimentation rate is high and the decay of the labile organic phosphorus is not fully realized before phosphorus-rich sediments from external loading build up over the alum floc. If the treatment dose for loosely bound, iron bound, and labile organic phosphorus is high, it is more effective and safer to split treatments across two or more events spaced one or more years apart. For Lake Kanasatka, an Al:P binding ratio of 20:1 is recommended to account for a portion of the labile organic phosphorus fraction.

- **The calculated areal dose by depth was averaged and assessed for the final areal dose.** Because of the inherent uncertainty in sediment results, the calculated dose is averaged for each depth interval. Taking minimum or maximum values would likely result in under or overestimates. The average calculated dose for each depth interval can then be assessed for grouping or simplification opportunities when doses are within 5-10 g/m2 or if treated shallower areas with lower calculated doses could distribute alum floc to deeper areas with higher calculated doses over time as sediments migrate (a.k.a, alum focusing). Higher doses for deeper areas should be maintained, however, if hypolimnion phosphorus is able to reach the photic zone and support cyanobacteria growth. This should not be an issue for deep, stratified lakes deeper than 18 meters (60 feet), which is not the case for Lake Kanasatka. It is usually most important to be sure that shallower areas are adequately treated to reduce phosphorus availability to cyanobacteria that can interact with the sediment-water interface and rise to form blooms. Areal doses of alum at other lakes around the world have generally ranged from 10 to 200 g/m^2, with most being less than 100 g/m^2 and more typically around 50 g/m^2 in New England. For Lake Kanasatka, the areal dose of alum was calculated as 56, 57, 57, and 79 g/m2 for depths 7.5-9, 9-11, 11-13, and 13+ meters, respectively (Table 6). We recommend that a uniform areal dose of 55 g/m2 be applied to all depths in the treatment area, assuming that the alum floc in shallower areas will drift to the deeper areas and increase the areal dose at the deepest spot over time (Table 6). The recommended areal dose of 55 g/m^2 for Lake Kanasatka will be protective of the lake without overtreating, given the available information[7].

[7] Sediment assays can be used to generate a curve of diminishing return on phosphorus mass reduction for each increment of alum dose applied. Compared to stoichiometric calculations based on sediment phosphorus fractionation, sediment assays can give a more direct measure of the appropriate areal dose range for a given lake and minimize uncertainty when considering the labile organic phosphorus fraction. This approach can help prevent over or underestimates of the appropriate areal dose of alum needed.

Table 6. Calculated and final recommended areal dose and planning level cost of alum by depth and mobile phosphorus fractions for Lake Kanasatka.

Depth zone (m)	Area (acres)	Loosely Sorbed and Fe-P			Labile Organic P			Total Mobile P		
		P mass (kg)	Al Dose (g/m^2)	Est. Cost	P mass (kg)	Al Dose (g/m^2)	Est. Cost	P mass (kg)	Al Dose (g/m^2)	Est. Cost
Preliminary Calculated Areal Doses										
7.5-9	69.8	790	56	$211,565	1,297	23	$86,853	2,087	79	$298,418
9-11	62.3	719	57	$192,527	1,196	24	$80,088	1,915	81	$272,615
11-13	11.0	127	57	$34,045	211	24	$14,140	338	81	$48,185
13+	9.7	154	79	$41,126	175	22	$11,686	328	101	$52,812
Final Recommended Areal Doses										
7.5-13+	153	1,789	55	$453,900	2,879	25	$206,318	4,668	80	$660,218

Final Treatment Plan

The final alum treatment plan recommendation for Lake Kanasatka is to apply a total areal dose of 55 g/m^2 over a treatment area of 153 acres representing 7.5 m and deeper in spring 2024. The areal dose should be applied in multiple doses of 25 g/m^2 or less at least one day apart in any given zone to minimize aluminum toxicity risks to aquatic organisms (refer to the section on Ecological and Human Health Considerations and the Operations and Management Plan). The total mass of aluminum needed to inactivate the mobile phosphorus mass in sediment is estimated at 33,893 kg. The aluminum will be applied to the lake in two solutions, aluminum sulfate (alum) and sodium aluminate (aluminate), at a volumetric ratio of 2:1. Aluminate helps to stabilize pH between 6.0 and 8.5 during the treatment (refer to the section on Ecological and Human Health Considerations). The alum and aluminate solutions are expected to be 4.4% and 10.2% aluminum, respectively. Based on the total mass of aluminum needed and a 2:1 ratio of alum:aluminate, this equates to 66,791 gallons of alum and 33,395 gallons of aluminate to be added to Lake Kanasatka. The cost of this treatment is estimated to be $453,900, not including monitoring or outside consulting assistance.

Following the spring 2024 treatment, we recommend that monitoring be completed each summer according to the monitoring plan (see section on Monitoring Plan) to assess the efficacy of the alum treatment over time. If the efficacy of the alum treatment degrades sooner than expected, then we recommend a second alum treatment be applied at an areal dose of 25 g/m^2 over a treatment area of 153 acres representing 7.5 m and deeper in spring (though additional sediment samples should be collected to confirm the calculated dose for a possible second treatment). The second treatment would treat the labile organic phosphorus fraction not directly targeted in the first treatment. The general practice for alum treatments is to split the dose if it is relatively high, which for New England tends to fall within 50 to 75 g/m^2, and wait a year or more in-between treatments. This approach allows the first treatment to be more affordable, lowers the risk to aquatic organisms in both treatments, and allows the additional dose in the second treatment to be more effective than if combined with the first treatment. The second treatment strips the water column of phosphorus for a second time and treats newly settled phosphorus from the external load or newly decayed phosphorus in the sediment since the first treatment.

The areal dose of 55 g/m^2 for Lake Kanasatka is comparable to other successful alum treatments completed in New England (Table 7). Major differences are Lake Kanasatka's larger watershed area, shorter water residence time, and lower internal phosphorus load percent contribution that may truncate the expected longevity of the treatment without further reductions in the external phosphorus load.

Table 7. General waterbody characteristics and treatment information for alum treatments completed in Maine and New Hampshire since 2018 compared to Lake Kanasatka (shaded grey). * indicates estimate.

Lake	East Pond	Georges Pond	Long Pond	Nippo Lake	Lake Kanasatka
Town, State	Oakland, ME	Franklin, ME	Parsonsfield, ME	Barrington, NH	Moultonborough, NH
Lake Area (acres)	1,717	358	263	85	353
Mean Depth (m)	5	4	6	6	6
Max Depth (m)	8	14	10	16	14
Watershed Area (acres)	2,832	636	832	294	4,176
Water Residence Time (yr)	2.5	2.0	2.0	2.5	1.0
Internal P Load (%)	49%	56%	32%	34%	20%
Treatment Year	2018	2020-21	2022	2022	2024
Treatment Depth (m)	>5	>5	>7	>4.6	>7.5
Treatment Area (acres)	676	131	89	56	153
Treatment Area (% of lake)	39%	37%	34%	66%	43%
Al Dose (g/m^2)	45	45	25, 40, 50	54	55
Treatment Cost	$1,100,000	$241,002	$218,075	$110,000*	$453,900*
Treatment Cost ($/g-m^2/ac)	$56	$41	$61	$36*	$54*

Expected Water Quality Outcomes

Immediate water quality improvements can be expected following the alum treatment of Lake Kanasatka. The alum floc strips phosphorus from the water column as it migrates down to the sediment where it binds with mobile phosphorus. In the first summer assuming a non-extreme weather year, Lake Kanasatka will likely experience record high water clarity and minimal to no cyanobacteria accumulations or blooms from the reduction in available phosphorus.

In the long-term according to model prediction scenarios, the average total phosphorus concentration will reduce by 1.4-1.8 µg/L to 8.6-9.0 µg/L, average water clarity will deepen by 0.5-0.6 m, average chlorophyll-a concentration will reduce by 0.6-0.7 µg/L to 2.6-2.7 µg/L, peak chlorophyll-a concentration will reduce by 2.0-2.6 µg/L to 9.4-10.0 µg/L, and bloom probability will reduce by at least 5-6 days (Table 8). The model did not predict well (underpredicted) for water clarity and bloom probability; thus, water quality improvements are expected to be better than predicted for those parameters.

Overall, through the significant reduction of cyanobacteria biomass, alum treatments have been shown to shift biological communities in favor of more balanced food webs (see section on Ecological and Human Health Considerations). The reduction in cyanobacteria biomass that dies and settles in the sediment can lessen oxygen demand and might help to decelerate the expansion of anoxic area in Lake Kanasatka, further benefiting treatment longevity. Better water clarity following treatments has also increased aquatic plant growth in littoral areas, so careful watch for invasive species is important.

It is important to understand that alum treatments are temporary management measures to control internal phosphorus loads that come from legacy external phosphorus loads. Without substantial reductions in the external phosphorus loads, phosphorus will continue to build up in newly deposited sediment and begin to release again as internal phosphorus load. Thus, the expected water quality improvements will deteriorate over time until the internal phosphorus load returns to pre-treatment magnitude. The next section discusses the anticipated treatment longevity for Lake Kanasatka.

Table 8. In-lake water quality model predictions for internal phosphorus (P) load reduction scenarios (90%, 80%, and 70%) compared to the current (2022) model prediction. The difference between 70% and 90% internal P load reduction scenarios (or uncertainty in expected water quality improvement) is compared to the predicted water quality improvement following external P load reduction achieved between 2021 and 2023. Note: Secchi disk transparency and bloom probability were not well predicted by the model (observed 2022 data showed an average of 5.4 m and 92 days, respectively).

Parameter	Current (2022)	90% Internal P Load Reduction	80% Internal P Load Reduction	70% Internal Load Reduction	70%-90% Difference	Plus 12.3 kg/yr External P Load Reduction
Total Phosphorus (µg/L)	10.4	8.6	8.8	9	0.4	-0.5
Secchi Disk Transparency (m)	3.8	4.4	4.4	4.3	-0.1	0.2
Mean Chlorophyll-a (µg/L)	3.3	2.6	2.7	2.7	0.1	-0.1
Peak Chlorophyll-a (µg/L)	12	9.4	9.7	10	0.6	-0.6
Bloom Probability (days)	8	2	3	3	1	-1

Treatment Longevity

A multitude of factors can influence alum treatment longevity. For instance, alum treatments of shallow polymictic lakes tend to have less longevity than deep stratified lakes. The presence of benthic feeding invertebrates and fish, such as carp, has also been shown to reduce the efficacy of alum treatments due to bioturbation of the sediment. Lakes with steep bathymetry or large fetches may concentrate the alum floc in one or more locations in the lake, leaving other areas without treatment over time.

There are a few approaches to estimating alum treatment longevity. One approach uses a partition model-based decision tree[8] built on thresholds from three important variables that best predict treatment longevity[9] (Huser et al., 2016). The three variables with the most explanatory power (82%) include the aluminum dose, the watershed to lake area ratio, and the Osgood index (Osgood, 1988). Treatment longevity was greatest in lakes with higher aluminum doses that effectively bound the mobile phosphorus fraction, longer water residence times (less flushing and dominance of internal load), and greater water column stability. The aluminum to mobile phosphorus ratio was also important but data were too limited to include in the final model. The model was significantly improved when shallow polymictic lakes with large populations of benthic feeding fish such as carp were excluded. Huser et al. (2016) found an average treatment longevity of 15-21 years for deep stratified lakes and 5-6 years for shallow polymictic lakes.

Running Lake Kanasatka's characteristics through the decision tree shows an alum treatment longevity of up to 23 years. Lake Kanasatka has a low Osgood index of 4.9 because of its large littoral area relative to lake surface area (and thus low mean depth). Lake Kanasatka would be considered a shallow polymictic lake according to the Osgood index (<6). Knowing that Lake Kanasatka is a deep stratified lake, we bypassed the Osgood index in the decision tree.[10] The difference between a longevity estimate of 23 years compared to 44 years came down to the

[8] The partition-based decision tree developed by Huser et al. (2016) was built on a database of 114 lakes treated with alum or a combination of alum and sodium aluminate. Study lakes represent a range in factors related to morphology, hydrology, applied dosage, and baseline chemistry in several US states (Florida, Maine, Michigan, Minnesota, New Hampshire, Vermont, Washington, and Wisconsin), as well as international countries (Denmark, Sweden, Germany).

[9] Huser et al. (2016) defined treatment longevity as the last year whereby 50% or greater improvement in water quality was maintained (preceded by at least two successive years of less than 50% improvement in water quality).

[10] Bypassing the Osgood index in the decision tree is further justified by the fact that the Osgood index had only 3% explanatory power in the model.

watershed to lake area ratio, which is high for Lake Kanasatka. A high watershed to lake area ratio indicates a shorter water residence time (more flushing and dominance of external load). This is unsurprising given that the internal phosphorus load to Lake Kanasatka was estimated to be only 20% of the total phosphorus load. Thus, the alum treatment longevity for Lake Kanasatka will likely be shorter than other alum treatments performed on deep stratified lakes in Maine and New Hampshire given these unique characteristics. Hypervigilance to continually reduce the external phosphorus load to Lake Kanasatka will be critical to maximizing the alum treatment's effective lifespan.

ECOLOGICAL AND HUMAN HEALTH CONSIDERATIONS

A review of the available literature on the effects of alum treatments on aquatic organisms, namely fish, amphibians, and invertebrates, shows that advancements in treatment technology over time have greatly improved the safety and efficacy of treatments, which are now considered a proven in-lake management option for internal phosphorus load control.

As an example of early applications in the late 1980s, an alum treatment conducted on Lake Morey, VT led to a decrease in the size quality of yellow perch due to sublethal aluminum toxicity when dissolved aluminum concentrations exceeded the 50 µg/L[11] target safety level recommended by Cooke & Kennedy (1981)[12] for both aquatic life and human consumption. Dissolved aluminum concentrations up to 200 µg/L were present at certain depths for a period of 30 days following the Lake Morey alum treatment (Smeltzer et al., 1999). Both short-term declines in zooplankton abundance and longer-term change in the relative composition of zooplankton communities following alum treatments have also been observed (Shumaker et al., 1993). Additionally, benthic macroinvertebrate populations have been shown to decline at certain depths one-year post alum treatment, but populations recovered within two years and ultimately increased in density and species richness as a longer-term response (Smeltzer et al., 1999).

A comprehensive synthesis by Cooke et al. (2005) places earlier treatments in the context of decades of additional experience with real-world application using many advancements in safety. The authors point out that continuous exposure experiments in mesocosms are not realistic tests of the effect of alum treatment on fish in a lake. In practice, fish are only impacted in the mixing zone of a treatment (see the section on Operations and Management Plan) or when floc falls through the water column since most fish can move and avoid toxic concentrations of aluminum (Cooke et al., 2005). As the base of the food chain for other fish, smelt are one fish species of particular concern due to their presence in open waters at depths that coincide with the mixing zone before the alum is dispersed and diluted. Aluminum concentrations tend to be highest and most toxic in the mixing zone before aluminum hydroxides and flocs have fully formed (Gensemer & Playle, 1999). Fortunately, once the alum floc has formed, lake chemistry has a blunting effect on any potential toxicity of aluminum on aquatic organisms, as the presence of total organic carbon and hardness (particularly calcium ions) will form organic ligands with aluminum and reduce or eliminate aluminum toxicity (Cooke et al., 2005). Overall, the risk to aquatic organisms is minimal and focused largely on immobile or low mobility aquatic organisms such as freshwater mussels, zooplankton, or phytoplankton in treatment areas. Short-term impacts to these populations often lead to more balanced food webs in the long-term (Wagner et al., 2017).

[11] Maximum contaminant levels for aluminum are set between 50 and 200 µg/L by the EPA for public drinking water systems, which regularly use aluminum as a binder to clarify finished water.

[12] In experimental mesocosms, Freeman & Everhart (1971) found that rainbow trout mortality and growth were significantly impacted by total aluminum concentrations as low as 520 µg/L in water at a pH of 7 to 9. Based in part on this work, Cooke & Kennedy (1981) produced an EPA study recommending a target safety level of 50 µg/L in water.

Additionally, aluminum will be applied in deep, offshore areas of the lake so there is little to no risk to human health even if some shorefront residents draw water directly from the lake for residential use during or after the treatment. Public notice of the treatment will be issued one week prior to the treatment through one week post treatment. Groundwater will not be affected so there is no risk of well contamination.

In summary, despite demonstrated impacts to aquatic organisms in certain experimental and real-world aluminum exposures, alum treatment is widely accepted as a beneficial water quality restoration and management tool for internal phosphorus load control. Through careful application, minor short-term impacts to aquatic life following an alum treatment are considered an acceptable trade-off for the massive ecological disruptions and health concerns caused by recurrent cyanobacteria blooms. The North American Lake Management Society (NALMS) holds the position that treating a lake with alum to control phosphorus is a "safe and effective" management tool so long as the treatment is designed and controlled to limit concerns with toxicity to aquatic life (NALMS, 2004). To reduce the impact on the environment and aquatic organisms, alum should be applied at a dose that minimizes effects to aquatic organisms. There are several alum treatment protective measures that can prevent toxicity during applications in New England lakes and ponds:

1) Control pH between 6.0 and 8.5[13]. During treatment, alum is injected into the lake just below the water surface. The alum quickly hydrolyzes to form a solid precipitate of aluminum hydroxide or alum floc, which is the active ingredient in over-the-counter antacids. The alum floc binds with phosphorus as it moves down through the water column and settles on the sediment within hours. The hydrogen ions released during that process can lower the pH of water. pH less than 6.0 allows aluminum to become soluble, which can be toxic to organisms, so maintaining pH above 6.0 and as close to baseline levels as possible avoids aluminum toxicity concerns during treatment. Sodium aluminate, which raises pH, is added in a 2:1 ratio of alum:aluminate to counteract and balance pH within the optimum range of 6.0 to 8.5 to avoid toxic effects. New England lakes are particularly vulnerable to acidification during treatment, given their naturally low pH. It is important for the applicator to adjust this ratio in real-time in response to pH changes in the lake as the treatment proceeds.

2) Avoid treating areas with a high dose and more than one pass on consecutive days. The applicator divides the treatment area into zones, usually representing up to a quarter of the total treatment area. To keep the concentration of aluminum in the mixing zone to 5 mg/L or less[14], no more than 25 g/m^2 is applied in one pass and no less than 24 hours is elapsed between passes in the same zone if more than one pass is needed to achieve the target dose (Wagner et al., 2017). The zones from upwind to downwind are rotated daily during the application period to minimize toxicity potential and allow mobile aquatic organisms to seek refuge away from the treatment area. Less than half (43%) of Lake Kanasatka will be treated, providing opportunities for mobile aquatic organisms to move out to non-treatment areas. The total target dose should also aim to be no more than 50 to 75 g/m^2 in a single treatment period; additional doses should be applied the following year or later. The alum treatment of Nippo Lake in 2021 found that impacts to young-of-the-year fish were minimized when consecutive parallel treatment passes were skipped, with untreated lanes treated later in the day once the floc had settled.

3) Conduct monitoring that evaluates key water quality and biological parameters. Monitoring is completed before, during, and after the treatment to evaluate responses in key parameters such as pH, aluminum, and biological observations such as die-offs or fish gill abnormalities. The treatment can be stopped or resumed after adjustments are made to keep within acceptable water quality ranges for aquatic

[13] Aluminum is toxic to organisms at concentrations of 0.1 to 0.2 mg/L under acidic conditions (pH < 5.5) when aluminum becomes highly soluble (Freda, 1991).

[14] Recommended for short-term alum treatments even though state and federal acute and chronic water quality criteria for total and dissolved aluminum are much lower. See the section on Operations and Management Plan.

life. The toxicity of aluminum at certain concentrations changes depending on the amounts of dissolved organic carbon and hardness present. Aluminum concentrations in the water return to background levels quickly after treatment so that recreation and even drinking water activities can resume right away if ever curtailed during treatment.

4) Treat under environmental conditions conducive to even distribution and proper mixing of the aluminum. Generally, spring is the best time in New England to complete an alum treatment. Treating during cyanobacteria blooms or any other form of high particulate accumulation in the lake interferes with alum floc settling and should be avoided. Waiting for water temperatures in the mixing zone to be 12 degrees Celsius or warmer is ideal for good floc formation, minimizing the dissolved aluminum exposure time for aquatic organisms. Treatment during non-stratified periods such as in spring when water is cooler and more oxygenated also allows organisms to move more freely around the lake to avoid the treatment area. Wind and rain are also considered (see the section on Operations and Management Plan).

OPERATIONS AND MANAGEMENT PLAN

For this project, the hired applicator will provide a more detailed Standard Operating Procedure (SOP) for the alum treatment prior to permit application approval by NHDES and the anticipated treatment start date in mid-May 2024. Staging will likely occur at the public boat launch on Lake Kanasatka, but final staging location determination is pending on-site evaluations by the hired applicator.

In general, the applicator uses a treatment vessel or barge with a subsurface injection system that allows for controlled application and proper mixing of liquid aluminum sulfate and sodium aluminate at variable boat speeds. The barge position on the lake is managed by a global positioning and depth monitoring system that allows the operator to apply the treatment within the target area. The barge is loaded with the aluminum from onshore storage tanks following procedures and response protocols that minimize environmental impacts from possible spills. The applicator applies the aluminum sulfate and sodium aluminate at a 2:1 ratio that results in a pH between 6.0 and 8.5, with a preferred range of 6.5 to 7.5 and an average pH target of 7.0 (Tables 9, 10). The applicator is responsible for real-time ratio adjustment to maintain the pH within the desired range.

Chemicals are simultaneously distributed by means of a dual manifold or other appropriate injection system that results in a mixing zone of suitable depth (assumed to be five vertical meters unless otherwise documented by the applicator). The applicator applies the aluminum in a pattern that leads to uniform distribution of alum floc on the bottom in the target area with minimum drift outside the target area. The application rate is such that the calculated concentration of aluminum in the mixing zone will not exceed 5 mg/L of aluminum, corresponding to a maximum daily dose of 25 g/m^2 and a maximum total dose of 55 g/m^2 (Tables 9, 10; Wagner et al., 2017). Where an area must be treated more than once to achieve the target dose, at least 24 hours must elapse between treatments of the same area. Table 10 includes suggested limits for total and dissolved aluminum based on criteria established by EPA and NHDES[15], respectively, for both chronic and acute conditions. Even with careful application, chronic and acute criteria limits for aluminum are often exceeded in the short-term, but the toxicity of applied aluminum is greatly curtailed by maintaining pH between the desired range of 6.0 and 8.0. Turbidity limits are also included as one means of assessing and minimizing the impact of physical alum floc presence on biota.

[15] Water quality criteria have been established to minimize the likelihood of impacts to aquatic life. Current NHDES acute and chronic criteria are 750 µg/L (1-hour average) and 87 µg/L (4-day average), respectively, for the acid soluble or dissolved aluminum fraction (NHDES administrative rule Env-Wq 1700). In 2018, EPA published updated aluminum water quality criteria which depend on pH, hardness, and dissolved organic carbon (EPA-822-R-18-001). The criteria are conservative in nature and are based on minimizing impacts to 95% of aquatic organisms and events that occur once per year (EPA-822-R-18-001).

Application can occur after ice-out but not until the lake is a minimum of 4.4 degrees Celsius throughout the water column and ideally 12 degrees Celsius within the mixing zone for good floc formation. Application of aluminum should not occur when wind speeds 6 feet above the lake surface exceed 15 mph. Application of aluminum should also be avoided when a significant precipitation is expected during treatment, but this is left up to the judgment of the applicator. It is most effective to perform alum treatments in the spring when water temperatures are warm enough for good floc formation and cyanobacteria bloom risk is low; otherwise, cyanobacteria blooms would interfere with alum floc settling. Treatment during non-stratified periods such as in spring when water is cooler and more oxygenated also allows organisms to move more freely around the lake to avoid the treatment area. Treatment zones representing one quarter (25%) or less of the total treatment area should be rotated daily during the application period to avoid toxicity concerns and provide refuge for mobile aquatic organisms. One approach used in other treatments is to complete the first dose on a Friday, monitor through the weekend, make any adjustments, and resume treatment on Monday or have a couple rest days mid-treatment.

Table 9. Surface water quality permit limits for aluminum compound additions to Lake Kanasatka.

Chemical Additive	Approx. Ratio of Application	Max daily dose (g/m^2)	Max total dose (g/m^2)
Aluminum Sulfate ($Al_2(SO_4)_3$) Sodium Aluminate ($NaAlO_2$)	2:1 alum:aluminate	25	55

Table 10. Surface water quality permit limits for receiving water quality criteria for Lake Kanasatka.

Parameter	Active Treatment Daily Event Maximum (Acute)	Active Treatment 4-Day Average (Chronic)	Post Treatment Daily/Weekly Average (Chronic)
Dissolved aluminum (µg/L)	750	87	Baseline
Total aluminum (µg/L)	Depends on pH, hardness, DOC	Depends on pH, hardness, and DOC	Baseline
Turbidity	10 NTU above baseline	10 NTU above baseline	Baseline
pH	6.0-8.0	6.0-8.0	Baseline

MONITORING PLAN

As discussed in the section on Ecological and Human Health Considerations, monitoring of key water quality and biological parameters before, during, and after treatment is necessary to ensure a successful alum treatment. Table 11 provides a detailed list of parameters to be measured, the timing of measurements, and the locations of measurements to be taken. Additional monitoring elements or sample location may be included as permit conditions. LKWA is responsible for contracting a qualified third-party monitor to carry out the monitoring plan.

Pre-Treatment Monitoring

Pre-treatment monitoring will include sampling at the three deep spots of the lake no more than three weeks prior to the start of the treatment. Results from the first sampling event will be made available to NHDES for review prior to the treatment. The following sampling will be conducted by a third-party monitor:

- Field measurements of temperature, dissolved oxygen, pH, turbidity, and specific conductance will be measured at 1-meter depth intervals.
- Secchi disk transparency readings will be collected.

- At 1-, 3-, 5-, 7-, 9-, 11-, and 13-meters depth, grab samples will be collected and submitted for laboratory analysis of alkalinity, hardness, dissolved organic carbon, acid soluble or dissolved aluminum, total aluminum, total phosphorus, total Kjeldahl nitrogen, and nitrate-nitrite.
- Mid-meta cores[16] will be collected for chlorophyll-a and phytoplankton analysis.
- Mid-meta tows will be collected for zooplankton analysis.
- A shoreline survey for any distressed organisms will also be conducted prior to treatment to set a baseline.

During Active Treatment Monitoring

During active treatment, an on-site third-party monitor will collect water quality and environmental data from a separate vessel. All data will be available to the applicator as quickly as possible, with field measurements available the same day as collected. The third-party monitor will communicate immediately with the applicator if any problems are indicated, including high or low pH, fish kills, or other negative impacts that may require cessation and/or modification of the treatment protocol. Daily monitoring plans may be altered (with NHDES approval) depending on conditions and applicator or third-party monitor preference, equipment, and past experiences.

In the morning of each treatment day prior to the start of treatment by the applicator (as well as the day after the final treatment), the approximate deepest middle area of each treatment zone (aiming to combine with the three deep spots of the lake) will be sampled by a third-party monitor for the following:

- Field measurements of temperature, dissolved oxygen, pH, turbidity, and specific conductance will be measured at 1-meter depth intervals.
- Secchi disk transparency readings will be collected.
- At 1-, 3-, 5-, 7-, 9-, 11-, and 13-meters depth, grab samples will be collected and submitted for laboratory analysis of alkalinity, hardness, dissolved organic carbon, acid soluble or dissolved aluminum, and total aluminum. Maintaining grab sample monitoring at 2-meter depth intervals will inform assessments of maximum aluminum concentration duration exposure on biota.
- Mid-meta cores[16] will be collected for phytoplankton analysis.
- Mid-meta tows will be collected for zooplankton analysis.
- A treatment zone and shoreline survey for distressed organisms large enough to observe by eye or underwater camera will also be conducted. Surveyors will observe shoreline areas for fish, shellfish, snail, amphibian, and bird fatalities or behavioral abnormalities and other signs of potential aluminum or pH toxicity.

During active treatment, a third-party monitor will follow behind the applicator in the aluminum plume (15 to 60 meters) and continuously monitor pH at about 2 meters depth. Evaluation of floc will be completed via an underwater camera to inspect floc formation and settling, as well as any noticeable distress to visible aquatic organisms. Within one to two hours of treatment, the deepest middle of the active treatment zone will be sampled by a third-party monitor for the following:

- Field measurements of temperature, pH, turbidity, and specific conductance will be measured at 1-meter depth intervals.
- At 1-, 3-, 5-, 7-, 9-, 11-, and 13-meters depth, grab samples will be collected and submitted for laboratory analysis of alkalinity, hardness, dissolved organic carbon, acid soluble or dissolved aluminum, and total aluminum. Maintaining grab sample monitoring at 2-meter depth intervals will inform assessments of maximum aluminum concentration duration exposure on biota.

[16] Tows for phytoplankton may be collected instead to match NHDES Volunteer Lake Assessment Program (VLAP) protocols.

- A treatment zone and shoreline survey for distressed organisms large enough to observe by eye or underwater camera will also be conducted. Surveyors will observe shoreline areas for fish, shellfish, snail, amphibian, and bird fatalities or behavioral abnormalities and other signs of potential aluminum or pH toxicity.

Post-Treatment Monitoring

Post-treatment monitoring will include sampling at the three deep spots of the lake within one week of the final treatment day and monthly thereafter through at least October, for a total of five sampling events. Monitoring will continue monthly during the growing season for two years following the year of treatment. The following sampling will be conducted by a third-party monitor:

- Field measurements of temperature, dissolved oxygen, pH, turbidity, and specific conductance will be measured at 1-meter depth intervals.
- Secchi disk transparency readings will be collected.
- At 1-, 3-, 5-, 7-, 9-, 11-, and 13-meters depth, grab samples will be collected and submitted for laboratory analysis of alkalinity, hardness, dissolved organic carbon, acid soluble or dissolved aluminum, total aluminum, total phosphorus, total Kjeldahl nitrogen, and nitrate-nitrite. Sample analysis for alkalinity, hardness, acid soluble or dissolved aluminum, total aluminum, dissolved organic carbon, and turbidity can cease once background levels are achieved following treatment.
- Mid-meta cores[17] will be collected for chlorophyll-a and phytoplankton analysis.
- Mid-meta tows will be collected for zooplankton analysis.
- A shoreline survey for any distressed organisms will also be conducted.

A report of all available data will be provided to NHDES within four months of treatment that includes the water quality data and details of the treatment.

We also recommend that volunteers continue biweekly monitoring of Secchi disk transparency and dissolved oxygen/temperature profiles at deep spot locations, as well as regular surveillance for cyanobacteria and invasive aquatic plants throughout the season.

[17] Tows for phytoplankton may be collected instead to match NHDES Volunteer Lake Assessment Program (VLAP) protocols.

Table 11. Proposed monitoring plan for Lake Kanasatka. Blue shaded parameters are field measurements; yellow shaded parameters are specific to treatment toxicity assessment; light yellow shaded parameters are nutrients important to tracking changes in internal loading and cycling; green shaded parameters are biological metrics; the grey shaded parameter is related to physical floc evaluation using a camera.

	Before Treatment	**During Treatment**			**After Treatment**
When	1-3 weeks before treatment starts (1 event)	AM daily pre-treatment + 1 day post-treatment	Active treatment	Within 1-2 hours of active treatment	Within 1 week after final treatment, monthly thereafter (5 events)
Where	3 deep spots	Middle/Deep of each treatment zone	In plume**	Middle/Deep of active treatment zone	3 deep spots
Secchi Disk Transparency ***	•	•			•
Profile (1-m intervals): Dissolved Oxygen/Temp ***	•	•			•
Profile (1-m intervals): Conductivity/pH/Temp/Turbidity^	•	•	•	•	•
Alkalinity (1, 3, 5, 7, 9, 11, 13 m) ^	•	•		•	•
Hardness (1, 3, 5, 7, 9, 11, 13 m) ^	•	•		•	•
Dissolved Organic Carbon (1, 3, 5, 7, 9, 11, 13 m) ^	•	•		•	•
Total and dissolved aluminum (1, 3, 5, 7, 9, 11, 13 m) ^	•	•		•	•
Total Phosphorus (1, 3, 5, 7, 9, 11, 13 m)	•				•
Total Kjeldahl Nitrogen (1, 3, 5, 7, 9, 11, 13 m)	•				•
Nitrate-Nitrite (1, 3, 5, 7, 9, 11, 13 m)	•				•
Chlorophyll-a (mid-meta core)	•				•
Phytoplankton (mid-meta core)	•	•			•
Zooplankton (mid-meta tow)	•	•			•
Fish & Aquatic Life [1]	•	•	•	•	•
Floc evaluation with camera			•	•	

*** continuously ~ 2 meters depth between 50' and 75' behind the barge*

**** aim for bi-weekly readings before and after treatment*

^ collection of monthly aluminum, alkalinity, hardness, DOC, turbidity samples may be discontinued once background levels of aluminum are achieved following treatment

[1] surveyors observe shoreline areas for fish, shellfish, snail, amphibian, and bird fatalities, insect hatches, and other signs of potential aluminum or pH toxicity, particular focus on downwind shoreline areas

REFERENCES

Cooke, G.D., and Kennedy, R.H. 1981. Precipitation and inactivation of phosphorus as a lake restoration technique. EPA-600/3-81-012, Corvallis Environmental Research Laboratory, US Environmental Protection Agency, Corvallis, Oregon, USA.

Cooke, G.D., E.B. Welch, S.A. Peterson, and S.A Nichols. 2005. Restoration and Management of Lakes and Reservoirs, Third Edition. Taylor and Francis, Boca Raton, Fl.

FBE. 2022a. Lake Kanasatka Watershed-Based Management Plan. Prepared by FB Environmental Associates (FBE) for Lake Kanasatka Watershed Association, August 16, 2022.

FBE. 2022b. Lake Kanasatka Lake Loading Response Model Report. Prepared by FB Environmental Associates (FBE) for Lake Kanasatka Watershed Association, July 2022.

FBE. 2023a. Technical Memorandum: Lake Kanasatka Data Review and Model Update. Prepared by FB Environmental Associates (FBE) for Lake Kanasatka Watershed Association, April 10, 2023.

FBE. 2023b. Technical Memorandum: Lake Kanasatka In-Lake Treatment Assistance – External Load Reduction Calculations. Prepared by FB Environmental Associates (FBE) for Lake Kanasatka Watershed Association, December 6, 2023.

Freeman, R.A., and Everhart, W.H. 1971. Toxicity of aluminum hydroxide complexes in neural and basic media to Rainbow Trout. Trans. Amer. Fish. Soc., 4: 644-658.

Gensemer, R.W., and Playle, R.C. 1999. The Bioavailability and Toxicity of Aluminum in Aquatic Environments, Critical Reviews in Environmental Science and Technology, 29:4, 315-450, DOI: 10.1080/10643389991259245

Huser, B.J., Egemose, S., Harper, H., Hupfer, M., Jensen, H., Pilgrim, K.M., Reitzel, K., Rydin, E., Futter, M. 2016. Longevity and effectiveness of aluminum addition to reduce sediment phosphorus release and restore lake water quality. Water Res., 97:122–132.

James, W.F., and Bischoff, J. 2015. Relationships between redox-sensitive phosphorus concentrations in sediment and the aluminum:phosphorus binding ratio. Lake and Reservoir Management, 31:339-346.

Jensen, H.S., Reitzel, K., and Egemose, S. 2015. Evaluation of aluminum treatment efficiency on water quality and internal phosphorus cycling in six Danish lakes. Hydrobiologia, 751:189–199.

McQuaid, A., and Craycraft, B. 2023. Lake Kanasatka and Wakondah Pond 2020-2022 Special Report. Prepared by the University of New Hampshire Extension Lakes Lay Monitoring Program.

NHDES. 2022a. State of New Hampshire 2020/22 Section 305(b) and 303(d) Consolidated Assessment and Listing Methodology (CALM). NHDES-R-WD-19-04. Retrieved from: https://www.des.nh.gov/sites/g/files/ehbemt341/files/documents/r-wd-20-20.pdf

NHDES. 2022b. New Hampshire's Watershed Report Cards built from the 2020/2022, 305(b)/303(d). Retrieved from: https://www4.des.state.nh.us/onestoppub/SWQA/010700020105_2020.pdf

NHDES. 2022c. Cyanobacteria Bloom History for Lake Kanasatka, Moultonborough, NH. Retrieved from: https://www4.des.state.nh.us/onestoppub/TrophicSurveys/Kanasatka.Moultonboro.Cyano.html

Norton, S.A., Coolidge, K., Amirbahman, A., Bouchard, R., Kopacek, J., and Reinhardt, R. 2008. Speciation of Al, Fe, and P in recent sediment from three lakes in Maine, USA. Science of the Total Environment, 404: 276-283.

Osgood R.A. 1988. Lake mixis and internal phosphorus dynamics. Arch. Hydrobiol., 113 (4):629-638.

Pilgrim, K.M., Huser, B.J., and Brezonik, P.L. 2007. A method for comparative evaluation of whole-lake and inflow alum treatment. Water Research, 41:1215-1224.

Reitzel, K., Hansen, J., Anderson, F.Ø., Hansen, K.J., Jensen, H.S. 2005. Lake restoration by dosing aluminum relative to mobile phosphorus in the sediment. Environ. Sci. Technol. 39, 4134–4140.

Rydin, E. and Brunberg, A. 1998. Seasonal dynamics of phosphorus in Lake Erken surface sediments. Arch. Hydrobiol. Spec. Issues Advanc. Limnol., 51:157-167.

Rydin, E., and Welch, E.B. 1998. Aluminum dose required to inactivate phosphate in lake sediments. Water Res., 32 (10):2969–2976.

Rydin, E., and Welch, E.B. 1999. Dosing alum to Wisconsin lake sediments based on in vitro formation of aluminum bound phosphate. Lake Reserv. Manage., 15 (4):324–331.

Rydin, E., Huser, B. and Welch, E.B. 2000. Amount of phosphorus inactivated by alum treatments in Washington lakes. Limnol. Oceanogr., 45:226-230.

Smeltzer, E., Kirn, R.A., and Fiske, S. 1999. Long-term Water Quality and Biological Effects of Alum Treatment of Lake Morey, Vermont. Journal of Lake and Reservoir Management, 15 (3):173-184.

Søndergaard, M., Jensen, J.P., and Jeppesen, E. 2003. Role of sediment and internal loading of phosphorus in shallow lakes. Hydrobiologia, 506-509:135-145.

Wagner, K.J., Meringolo, D., Mitchell, D.F., Moran, E., and Smith, S. 2017. Aluminum treatments to control internal phosphorus loading in lakes on Cape Cod, Massachusetts. Lake Reserv Manage., 33:171-186.

Welch, E.B., and Cooke, G.D. 1999. Effectiveness and longevity of phosphorus inactivation with alum. Lake Reserv. Manage. 15:5-27.

Welch, E.B., Gibbons, H.L., Brattebo, S.K., Corson-Rikert, H.A. 2017. Progressive conversion of sediment mobile phosphorus to aluminum phosphorus. Lake and Reservoir Management, 33(2), 205-210.

APPENDIX A: 2022 DISSOLVED OXYGEN-TEMPERATURE PROFILES

Table A1. Water temperature by 0.5-meter depth increments measured at the deep spot (1 Deep) of Lake Kanasatka for 12 dates from May to October 2022. Water temperature values are color coded from cool (blues) to warm (yellows) to warmest (orange, red). Italicized text represent values that were averaged from the sample dates immediately before and after.

Depth (meters)	5/20/22 (°C)	6/6/22 (°C)	6/20/22 (°C)	7/8/22 (°C)	7/14/22 (°C)	7/28/22 (°C)	8/9/22 (°C)	8/19/22 (°C)	8/31/22 (°C)	9/9/22 (°C)	9/21/22 (°C)	10/7/22 (°C)
0.1	16.1	20.5	19.8	24.8	25.2	26.4	29.4	24.3	26.0	22.6	20.2	16.6
0.5	16.2	20.5	19.8	24.7	25.2	26.5	29.5	24.2	26.1	22.6	20.2	16.6
1.0	16.2	20.4	19.8	24.6	25.2	26.4	29.5	24.2	26.1	22.6	20.2	16.5
1.5	16.0	20.3	19.9	24.5	25.1	26.4	29.4	24.2	26.0	22.6	20.2	16.4
2.0	16.0	20.2	19.8	24.5	25.1	26.5	29.4	24.2	26.0	22.6	20.2	16.4
2.5	15.9	20.2	19.8	24.4	25.1	26.4	29.4	24.2	25.9	22.7	20.1	16.3
3.0	15.8	20.2	19.8	24.3	25.1	26.4	29.3	24.1	25.7	22.7	20.1	16.2
3.5	15.7	20.0	19.8	24.3	24.9	26.4	29.1	24.1	25.7	22.7	20.1	16.2
4.0	15.4	19.9	19.8	24.1	24.3	26.4	28.0	24.1	25.7	22.7	20.0	16.2
4.5	15.1	19.7	19.8	23.9	24.0	26.4	27.8	24.1	25.7	22.7	20.0	16.2
5.0	14.6	19.6	19.7	23.6	23.4	26.0	26.8	24.1	25.6	22.7	20.0	16.2
5.5	14.2	17.2	19.7	23.2	23.0	24.9	26.1	24.1	25.2	22.7	20.0	16.1
6.0	13.7	16.3	18.9	20.8	20.7	22.5	24.9	24.0	25.0	22.7	20.0	16.1
6.5	13.0	14.6	17.4	18.0	17.3	21.0	21.8	24.0	23.3	22.6	20.0	16.0
7.0	12.6	13.6	15.6	17.6	17.0	18.4	22.1	22.2	22.6	22.6	20.0	16.0
7.5	12.3	13.2	14.1	16.1	16.0	16.9	21.8	18.7	19.3	22.3	20.0	16.0
8.0	11.8	12.9	13.4	14.9	14.9	16.1	17.7	17.5	17.8	19.6	20.0	15.9
8.5	11.5	12.7	12.8	14.1	14.3	15.2	16.2	15.8	17.1	17.4	20.0	15.9
9.0	11.2	12.3	12.5	13.6	13.4	14.6	15.2	14.9	15.4	16.0	19.9	15.9
9.5	10.9	11.9	12.2	12.9	12.9	13.5	*13.9*	14.3	14.7	14.5	17.1	15.9
10.0	10.8	11.7	12.0	12.6	12.4	13.1	*13.2*	13.3	14.4	13.4	14.0	15.9
10.5	10.5	11.4	11.3	12.3	11.7	12.3	*12.5*	12.6	13.1	12.8	13.1	15.8
11.0	10.3	10.9	10.9	11.7	11.4	11.1	*11.6*	12.1	12.4	12.2	12.5	15.7
11.5	10.2	10.5	10.7	11.4	11.1	11.0	*11.3*	11.5	11.8	11.6	12.2	15.6
12.0	10.1	10.3	10.6	11.3	10.9	10.8	*11.0*	11.2	11.6	11.4	12.0	15.0
12.5	10.0	10.2	10.4	10.9	10.9	10.6	11.8	10.8	11.3	11.0	11.2	12.5
13.0	9.9		10.4	10.8	10.5		11.6	10.7	11.1	10.7	11.0	11.1
13.5	9.7		10.2	10.6	10.5		11.4		10.9		10.9	

Table A2. Dissolved oxygen concentration by 0.5-meter depth increments measured at the deep spot (1 Deep) of Lake Kanasatka for 12 dates from May to October 2022. Dissolved oxygen concentration values are color coded from well oxygenated (blues) to moderately oxygenated (yellow) to poorly oxygenated (reds). Italicized text represent values that were averaged from the sample dates immediately before and after.

Depth (meters)	5/20/22 (mg/L)	6/6/22 (mg/L)	6/20/22 (mg/L)	7/8/22 (mg/L)	7/14/22 (mg/L)	7/28/22 (mg/L)	8/9/22 (mg/L)	8/19/22 (mg/L)	8/31/22 (mg/L)	9/9/22 (mg/L)	9/21/22 (mg/L)	10/7/22 (mg/L)
0.1	9.8	9.2	8.9	8.5	8.4	8.1	7.3	7.9	8.2	8.4	7.9	9.4
0.5	9.8	9.2	8.9	8.5	8.4	8.1	7.3	7.9	8.2	8.3	7.8	9.4
1.0	9.8	9.2	8.8	8.5	8.4	8.1	7.3	7.9	8.2	8.3	7.8	9.4
1.5	9.8	9.2	8.8	8.5	8.4	8.1	7.3	7.9	8.2	8.3	7.8	9.5
2.0	9.8	9.2	8.8	8.5	8.4	8.1	7.3	7.9	8.2	8.3	7.8	9.5
2.5	9.8	9.2	8.8	8.5	8.4	8.1	7.3	7.9	8.2	8.3	7.8	9.4
3.0	9.8	9.2	8.8	8.5	8.4	8.1	7.3	7.9	8.2	8.3	7.8	9.4
3.5	9.9	9.2	8.8	8.4	8.4	8.1	7.3	7.9	8.1	8.3	7.8	9.4
4.0	9.9	9.2	8.8	8.4	8.5	8.1	7.5	7.9	8.1	8.3	7.8	9.4
4.5	9.9	9.1	8.8	8.5	8.5	8.0	7.5	7.8	8.1	8.3	7.8	9.4
5.0	9.9	9.4	8.8	8.5	8.6	8.1	7.4	7.8	8.1	8.3	7.8	9.3
5.5	9.9	9.7	8.8	8.6	8.7	8.3	7.5	7.8	7.9	8.3	7.8	9.2
6.0	9.9	9.7	8.5	8.7	8.7	7.9	7.6	7.7	7.3	8.1	7.8	9.3
6.5	9.7	9.4	8.3	7.8	7.4	7.9	6.8	7.7	6.9	7.9	7.8	9.2
7.0	9.6	8.0	7.4	6.4	5.5	6.8	7.9	5.9	6.6	7.9	7.8	9.1
7.5	9.5	7.6	6.5	4.8	3.7	2.1	6.4	4.6	1.7	7.0	7.8	9.1
8.0	9.2	6.7	5.5	2.5	2.3	1.3	3.3	1.6	0.9	0.8	7.8	8.9
8.5	9.4	6.2	3.8	1.0	1.8	1.0	1.2	0.4	0.3	0.3	7.8	9.0
9.0	8.6	5.9	3.1	1.5	0.9	0.6	0.5	0.3	0.1	0.2	7.8	8.9
9.5	8.0	4.7	2.6	0.8	0.4	0.6	*0.4*	0.2	0.1	0.1	0.2	8.9
10.0	7.6	4.4	2.3	0.7	0.2	0.6	*0.3*	0.1	0.0	0.1	0.1	8.8
10.5	6.9	3.9	1.7	0.5	0.3	0.2	*0.2*	0.1	0.0	0.0	0.0	8.7
11.0	7.0	3.3	1.5	0.3	0.4	0.1	*0.1*	0.1	0.0	0.0	0.0	8.3
11.5	6.4	2.6	1.2	0.2	0.0	0.1	*0.1*	0.1	0.0	0.0	0.0	7.6
12.0	6.3	2.0	0.9	0.1	0.0	0.1	*0.1*	0.0	0.0	0.0	0.0	5.3
12.5	5.9	0.3	0.7	0.0	0.0	0.1	0.5	0.0	0.0	0.0	0.0	0.4
13.0	5.2		0.5	0.0	0.0		0.3	0.0	0.0	0.0	0.0	0.1
13.5	3.3		0.1	0.0	0.0		0.2		0.0		0.0	

APPENDIX B: ALTERNATIVES ANALYSIS REVIEW TABLE

Table B1: Alternatives analysis for Lake Kanasatka. Adapted from DKWRC-WRS (2020). Applicable alternatives are shaded.

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO LAKE KANASATKA
1) Management for nutrient input reduction	Includes wide range of watershed and lake edge activities intended to eliminate nutrient sources or reduce delivery to lake Essential component of algal control strategy where internal recycling is not the dominant nutrient source, and desired even where internal recycling is important	Acts against the original source of algal nutrition Creates sustainable limitation on algal growth May control delivery of other unwanted pollutants to lake Facilitates ecosystem management approach which considers more than just algal control	May involve considerable lag time before improvement observed May not be sufficient to achieve goals without some form of in-lake management Reduction of overall system fertility may impact fisheries May cause shift in nutrient ratios which favor less-desirable algae	Applicable, (see below for evaluation of input management alternatives)
1a) Point source controls	More stringent discharge requirements May involve diversion May involve technological or operational adjustments May involve pollution prevention plans	Often provides major input reduction Highly efficient approach in most cases Success easily monitored	May be very expensive in terms of capital and operational costs May transfer problems to another watershed Variability in results may be high in some cases	Not applicable – no point sources
1b) Nonpoint source controls	Reduction of sources of nutrients May involve elimination of land uses or activities that release nutrients May involve land conservation or other efforts to prevent future nutrient loading May involve alternative product use, such as no phosphate fertilizer May involve non-structural best management practices that include community outreach and education	Removes source of algal nutrition Limited ongoing costs May limit sources of other contaminants as well	May require purchase of land or remedial action on private property May be viewed as limitation of "quality of life" Has a delayed impact- lake recovery may take time during which cyanobacteria blooms may occur Usually requires education and gradual implementation	High applicability Essential to control both external and internal sources to reduce probability of algal blooms Can lower current loading and prevent future loading through policy change and outreach Control of external sources may increase longevity of any phosphorus inactivation program for internal loading Watershed plan details source reduction options

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO LAKE KANASATKA
1c) Nonpoint source pollutant trapping	Capture of pollutants between source and lake May involve drainage system alteration Often involves wetland treatments (det./infiltration) May involve stormwater collection and treatment as with point sources	Minimizes interference with land uses and activities Allows diffuse and phased implementation throughout watershed Highly flexible approach Tends to address wide range of pollutant loads	Does not address actual contaminant sources May be expensive on necessary scale May require substantial maintenance	Applicable Watershed plan includes detailed recommendations for several runoff mitigation sites
2) Circulation and destratification	Use of water or air to keep water in motion Intended to prevent or break stratification and oxygenate water Generally driven by mechanical or pneumatic force	Reduces surface build-up of algal scums May disrupt growth of cyanobacteria Counteraction of anoxia improves habitat for fish/invertebrates Can eliminate localized problems without obvious impact on whole lake Some solar powered and easily deployable proprietary devices are available Decreases water temperature in epilimnion which is less suitable for some cyanobacteria	May spread localized impacts May lower oxygen levels in shallow water and raise temperature in hypolimnion May promote downstream impacts May create localized mixing but may not have a substantial impact on a large waterbody May increase turbidity and decrease pH (Visser et al., 2016) May not necessarily decrease the internal load based on sedimentation and sediment characteristics (Gächter and Müller, 2003; Gächter and Wehrli, 1998) May impact boating / recreation	Not applicable May substantially increase photic zone total phosphorus due to large differences between epilimnion and hypolimnion TP and feed larger blooms Requires continual growing season use for foreseeable future Requires shore-based infrastructure May require considerable ongoing operational costs to move sufficient water to possibly suppress cyanobacteria Deep-mixing harms the growth of *Dolichospermum* (Visser et al., 2016) but favors other species such as *Planktothrix*
3) Dilution and flushing	Addition of water of better quality can dilute nutrients Addition of water of similar or poorer quality flushes system to minimize algal build-up May require continuous or periodic additions	Dilution reduces nutrient concentrations without altering load Flushing minimizes detention; response to pollutants may be reduced Flushing may decrease cyanobacteria biomass and toxin concentrations (Microcystis) (Romo et al., 2013)	Diverts water from other uses Flushing may wash desirable zooplankton from lake Use of poorer quality water increases loads Possible downstream impacts / not applicable during drought (Herman et al., 2017)	Not applicable Dilution/flushing would be needed during the time of year with the lowest water levels and would limit recreation

OPTION	**MODE OF ACTION**	**ADVANTAGES**	**DISADVANTAGES**	**APPLICABILITY TO LAKE KANASATKA**
4) Drawdown	Lowering of water over autumn period allows oxidation, desiccation, and compaction of sediments Duration of exposure and degree of dewatering of exposed areas are important Algae are affected mainly by reduction in available nutrients	May reduce available nutrients or nutrient ratios, affecting algal biomass and composition Opportunity for shoreline clean-up/structure repair Flood control utility May provide rooted plant control	Possible impacts on non-target resources Possible impairment of water supply (nearshore wells or downstream resources) Alteration of downstream flows and winter water level May accelerate sediment transport from the littoral zone to the deep spot (Shantz et al., 2004) May enhance release of nutrients upon rewetting (Carmignani and Roy, 2017) May result in greater nutrient availability if flushing inadequate	Not applicable Lake is already partially drawn down in the fall; any further drawdown would not address internal loading issue and may worsen P loading due to changing redox conditions and sedimentation
5) Dredging	Sediment is physically removed by wet or dry excavation, with deposition in a containment area for dewatering Dredging can be applied on a limited basis, but is most often a major restructuring of a severely impacted system Nutrient reserves are removed, and algal growth can be limited by nutrient availability	Can control algae if internal recycling is main nutrient source Increases water depth Can reduce pollutant reserves Can reduce sediment oxygen demand Can improve spawning habitat for many fish species Allows complete renovation of aquatic ecosystem	Temporarily reduces benthic invertebrate populations May create turbidity or reveal other buried sediment-bound contaminants or P-rich sediment May eliminate fish community (complete dry dredging only) Possible impacts from containment area discharge and dredged material disposal Interference with recreation or other uses during dredging Dredging is often ineffective without efforts to minimize watershed P (Bormans et al., 2015; Riza et al., 2023) Costly	Not applicable Large drawdown not possible, even if short term

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO LAKE KANASATKA
5a) "Dry" excavation	Lake drained or lowered to maximum extent practical Target material dried to maximum extent possible Conventional excavation equipment used to remove sediments	Tends to facilitate a very thorough effort May allow drying of sediments prior to removal Allows use of less specialized equipment	Eliminates most aquatic biota unless a portion left undrained Eliminates lake use during dredging Downstream impacts of drained water	Not applicable Large drawdown not possible, even if short term
5b) "Wet" excavation	Lake level may be lowered, but sediments not substantially exposed Draglines, bucket dredges, or long-reach backhoes used to remove sediment	Requires least preparation time or effort, tends to be least cost dredging approach May allow use of easily acquired equipment May preserve aquatic biota	Usually creates extreme turbidity Normally requires intermediate containment area to dry sediments prior to hauling May disrupt ecological function Disrupts recreational uses of the lake	Not applicable Lake is too large to manage with shore-based equipment
5c) Hydraulic removal	Lake level not reduced Suction or cutterhead dredges create slurry which is hydraulically pumped to containment area Slurry is dewatered, sediment retained, water discharged	Creates minimal turbidity and impact on biota Can allow some lake uses during dredging Allows removal with limited access or shoreline disturbance	Often leaves some sediment behind Cannot handle coarse or debris-laden materials Requires sophisticated and more expensive containment area Costly	Not applicable No large staging area near shore Pumping hydraulically dredged sediments uphill to a potential staging area would be a challenge Quality of sediments for disposal is unknown
6) Light-limiting dyes and surface covers	Creates light limitation	Creates light limit on algal growth without high turbidity or great depth Can limit photochemical reactions that degrade water quality (Herman et al., 2017) May achieve some control of rooted plants	May cause thermal stratification in shallow ponds Interferes with recreational uses May facilitate anoxia at sediment interface with water	Not applicable Lake is too large Artificial color would be objectionable Cover would eliminate recreation opportunities
6a) Dyes	Water-soluble dye is mixed with lake water, thereby limiting light penetration and inhibiting algal growth Dyes remain in solution until washed out of system	Produces appealing color Creates illusion of greater depth	May not control surface bloom-forming species May not control growth of shallow water algal mats May alter thermal regime	Not applicable Lake is too large Artificial color would be objectionable

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO LAKE KANASATKA
6b) Surface covers	Opaque sheet material applied to water surface Floating shade balls added to the water	Minimizes atmospheric and wildlife pollutant inputs Decreases evaporation thus maintaining more dilute epilimnion nutrient concentrations	Minimizes atmospheric gas exchange Limits recreation	Not applicable Lake is too large Cover would eliminate recreation opportunities
7) Mechanical removal	Filtering of pumped water for water supply purposes Collection of floating scums or mats with booms, nets, or other devices Continuous or multiple applications per year usually needed	Algae and associated nutrients can be removed from system; prevents additional DO depletion in hypolimnion after crash Surface collection can be applied as needed May remove floating debris Collected algae dry to minimal volume	Filtration requires high backwash and sludge handling capability Labor and/or capital intensive Variable collection efficiency Possible impacts on non-target aquatic life	Not applicable Photic zone volume is too large and algal populations grow too rapidly to effectively treat Would require complete treatment of photic zone every week or two Would need municipal scale physical plant on shore of lake to begin to be effective Capturing and removing cyanobacteria may also remove desirable zooplankton
8) Selective withdrawal	Discharge of bottom water which may contain (or be susceptible to) low oxygen and higher nutrient levels May be pumped or utilize passive head differential	Removes targeted water from lake efficiently May prevent anoxia and phosphorus build up in bottom water May remove initial phase of algal blooms which start in deep water May create coldwater conditions downstream	Possible downstream impacts of poor water quality May promote mixing of remaining poor quality bottom water with surface waters (Bormans et al., 2015) May cause unintended drawdown if inflows do not match withdrawal May have negative downstream impacts due to high phosphorus levels and low dissolved oxygen	Not applicable Would likely not be able to deplete hypolimnion without drawing down lake substantially in the summer due to large anoxic extent Potential use of hypolimnetic water for agriculture would export nutrients outside of the watershed and limit fertilizer use elsewhere Potential downstream impacts: high P and low DO water in the hypolimnion
9) Sonication	Sound waves disrupt algal cells	Supposedly affects only algae (new technique) Applicable in localized areas	Unknown effects on non-target organisms May release cellular toxins or other undesirable contents into water column	Not applicable Scale of lake is too large for this to be effective

OPTION	**MODE OF ACTION**	**ADVANTAGES**	**DISADVANTAGES**	**APPLICABILITY TO LAKE KANASATKA**
10) Hypolimnetic aeration or oxygenation	Addition of air or oxygen provides oxic conditions Maintains stratification Can also withdraw water, oxygenate, then replace	Oxic conditions reduce phosphorus availability Oxygen improves habitat Oxygen reduces build-up of reduced compounds May promote denitrification (N removal) from the system May reduce sediment oxygen demand from legacy organic matter (Preece et al., 2019)	May disrupt thermal layers important to fish community Theoretically promotes supersaturation with gases harmful to fish May not necessarily decrease the internal load based on sedimentation + sediment characteristics (Gächter and Müller, 2003; Gächter and Wehrli, 1998) May need to be used for 10+ years and paired with watershed load reductions to potentially see long-term, sustained impacts (Preece et al., 2019)	Possibly applicable If sized properly would reduce volume of anoxic water and may reduce legacy organic matter over time Would require continuous operation during stratification period and may need to be used for over 10 years to see sustainable results Has shore power and infrastructure needs Lake recovery from power outages or equipment malfunctions during stratification may not be possible during one season
11) Algaecides	Liquid or pelletized algaecides applied to target area Algae killed by direct toxicity or metabolic interference Typically requires application at least once per year, often more frequently	Rapid elimination of algae from water column, normally with increased water clarity May result in net movement of nutrients to bottom of lake	Possible toxicity to non-target species Restrictions on water use for varying time after treatment Increased oxygen demand Possible recycling of nutrients	Somewhat applicable (see below for discussion of specific algaecides)
11a) Forms of copper	Cellular toxicant, disruption of membrane transport Applied as wide variety of liquid or granular formulations	Effective and rapid control of many algae species Approved for use in most water supplies	Possible toxicity to aquatic fauna Accumulation of copper in system Resistance by certain green and blue-green nuisance species Lysing of cells releases nutrients and toxins and increases oxygen demand	Somewhat applicable Will reduce or eliminate an existing bloom Won't appreciably change conditions that caused bloom so bloom conditions may re-occur in same season Will require application permit

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO LAKE KANASATKA
11b) Peroxides	Disrupts most cellular functions, tends to attack membranes Applied as a liquid or solid Typically requires application at least once per year, often more frequently	Rapid action Oxidizes cell contents, may limit oxygen demand and toxicity	Much more expensive than copper Limited track record Possible recycling of nutrients and increases oxygen demand	Somewhat applicable May work to reduce or eliminate an existing bloom but at high cost Won't appreciably change conditions that caused bloom so bloom conditions may re-occur in same season Requires an application permit
11c) Synthetic organic algaecides	Absorbed or membrane- active chemicals which disrupt metabolism Causes structural deterioration	Used where copper is ineffective Limited toxicity to fish at recommended dosages Rapid action	Non-selective in treated area Toxic to aquatic fauna (varying degrees by formulation) Time delays on water use May promote nutrient recycling and increased oxygen demand	Somewhat applicable Will reduce or eliminate an existing bloom Won't appreciably change conditions that caused bloom so bloom conditions may re-occur in same season Will require application permit May have waterbody use restrictions
11d) Iron-nanoparticles	High concentrations of iron nanoparticles can disrupt cell division and affect photosynthesis in phytoplankton	May decrease photosynthetic activity after 7 days Potentially toxic to cyanobacteria	May increase photosynthesis in short-term after treatment (>3 days) (D'ors et al., 2023) May impact non-nuisance phytoplankton species Impacts are only short term due to iron oxidation (D'ors et al., 2023)	Not applicable May impact non-nuisance phytoplankton species Limited data to support methods Short term impacts

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO LAKE KANASATKA
12) Phosphorus inactivation	Typically salts of aluminum, iron, or calcium are added to the lake, as liquid or powder Phosphorus in the treated water column is complexed and settled to the bottom of the lake Phosphorus in upper sediment layer is complexed, reducing release from sediment Permanence of binding varies by binder in relation to redox potential and pH May involve using lanthanum-modified clay and flocculant (PhosLock)	Can provide rapid, major decrease in phosphorus concentration in water column Can minimize release of phosphorus from sediment May remove other nutrients and contaminants as well as phosphorus Flexible with regard to depth of application and speed of improvement Can provide long-term phosphorus reductions if paired with watershed management activities	Possible toxicity to fish and invertebrates, especially by aluminum at low pH Possible release of phosphorus under anoxia or extreme pH May cause fluctuations in water chemistry, especially pH, during treatment Possible resuspension of floc in shallow areas Adds to bottom sediment, but typically an insignificant amount	Applicable Hypolimnetic anoxia and pH suggest that aluminum would be the most appropriate compound to inactivate phosphorus Deep stratified lakes tend to have longer treatment durations (Huser et al., 2016) Water column phosphorus would be stripped during application
13) Sediment oxidation	Addition of oxidants, binders and pH adjustors to oxidize sediment Binding of phosphorus is enhanced Denitrification is stimulated	Can reduce phosphorus supply to algae Can alter nitrogen to phosphorus ratios in water column May decrease sediment oxygen demand	Possible impacts on benthic biota Longevity of effects not well known Possible source of nitrogen for cyanobacteria (Liu et al., 2017) Oxidized sediment (post-treatment) is lighter and more easily displaced, can reveal anoxic sediment underneath (Willenbring et al., 1984)	Possibly applicable Effects are not well understood and there are insufficient case studies to predict effectiveness with any degree of confidence Case studies have varying outcomes depending on biochemical properties of the sediment (Li and Shi, 2021)
14) Settling agents	Closely aligned with phosphorus inactivation, but can be used to reduce algae directly too Lime, alum, or polymers applied, usually as a liquid or slurry Creates a floc with algae and other suspended particles Floc settles to bottom of lake Re-application typically necessary at least once per year	Removes algae and increases water clarity without lysing most cells Reduces nutrient recycling if floc sufficient Removes non-algal particles as well as algae May reduce dissolved phosphorus levels at the same time	Possible impacts on aquatic fauna Possible fluctuations in water chemistry during treatment Resuspension of floc possible in shallow, well-mixed waters Promotes increased sediment accumulation	See # 12 above. Technique refers to the water column phosphorus stripping that would occur during sediment treatment Will typically require re-treatment every year

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO LAKE KANASATKA
15) Selective nutrient addition	Ratio of nutrients changed by additions of selected nutrients Addition of non-limiting nutrients can change composition of algal community Processes such as settling and grazing can then reduce algal biomass	Can reduce algal levels where control of limiting nutrient not feasible Can promote non-nuisance forms of algae Can improve productivity and biodiversity of system without increased standing crop of algae	May result in greater algal abundance through uncertain biological response May require frequent application to maintain desired ratios Possible downstream effects Increased nitrogen may increase toxicity of cyanobacteria blooms in non-diazotrophic species (Gobler et al., 2016)	Not applicable Likely would involve adding nitrogen to favor species other than diazotrophic cyanobacteria Contrary to principles of watershed management Increasing nitrogen may favor non-diazotrophic cyanobacteria such as Microcystis and promote toxicity Nitrogen addition may result in additional algal growth of non- cyanobacteria species
16) Enhanced grazing	Manipulation of biological components of system to achieve grazing control over algae Typically involves alteration of fish community to promote growth of grazing zooplankton	May increase water clarity by changes in algal biomass or cell size without reduction of nutrient levels Can convert unwanted algae into fish Harnesses natural processes	May involve introduction of exotic species Effects may not be controllable or lasting May foster shifts in algal composition to even less desirable forms	Somewhat applicable (see below for specific alternatives to support enhanced grazing) Most applicable for shallow lakes (Søndergaard et al., 2008)
16a) Herbivorous fish	Stocking of fish that eat algae	Converts algae directly into potentially harvestable fish Grazing pressure can be adjusted through stocking rate	Typically requires introduction of non-native species Difficult to control over long term Smaller algal forms may be benefited and bloom	Not applicable Not permitted in NH

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO LAKE KANASATKA
16b) Enhanced grazing through food chain interactions	Reduction in planktivorous fish to promote grazing pressure by zooplankton May involve stocking piscivores or removing planktivores May also involve stocking zooplankton or establishing refugia May involve restrictions on fishing piscivores May involve stocking *Daphnia*	May increase water clarity by changes in algal biomass or cell size without reduction of nutrient levels Converts algae indirectly into harvestable fish Zooplankton response to increasing algae can be rapid May be accomplished without introduction of non-native species Generally compatible with most fishery management goals	May involve introduction of exotic species Effects may not be controllable or lasting May foster shifts in algal composition to even less desirable forms Highly variable response expected; temporal and spatial variability may be high Requires careful monitoring and management action on 1-5 yr basis Larger or toxic algal forms may be benefitted and bloom May be ineffective without watershed load reductions (Kasprzak et al., 2007) Requires a large percentage of the fish stock to be piscivores (Kasprzak et al., 2007) Stocking adds additional nutrients to the system	Somewhat applicable Nuisance cyanobacterial species are generally not preferred by grazers Fish habitat may be limited by low dissolved oxygen Requires extensive and repeated removal/stocking of fish Effects may be most apparent when paired with reduced phosphorus loading, and may not be observed for years
17) Bottom-feeding fish removal	Removes fish that browse among bottom deposits, releasing nutrients to the water column by physical agitation and excretion May involve stocking piscivores	Reduces turbidity and nutrient additions from this source May restructure fish community in more desirable manner	Targeted fish species are difficult to control Reduction in fish populations valued by some lake users (human/non-human)	Not applicable Bottom-feeding fish habitat is likely already reduced by anoxia
18) Microbial competition	Addition of microbes, often with oxygenation, can tie up nutrients and limit algal growth Tends to control nitrogen more than phosphorus	Shifts nutrient use to organisms that do not form scums or impair uses to same extent as algae Harnesses natural processes May decrease sediment	Minimal scientific evaluation Nitrogen control may still favor cyanobacteria May need aeration system to get acceptable results	Not applicable Favorable results for phosphorus control have not been documented

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO LAKE KANASATKA
19) Pathogens	Addition of inoculum to initiate attack on algal cells May involve fungi, bacteria, or viruses	May create lakewide "epidemic" and reduction of algal biomass May provide sustained control through cycles Can be highly specific to algal group or genera	Largely experimental approach at this time May promote resistant nuisance forms May cause high oxygen demand or release of toxins by lysed algal cells Effects on non-target organisms uncertain	Not applicable Experimental
20) Competition and allelopathy by plants	Plants may tie up sufficient nutrients to limit algal growth Plants may create a light limitation on algal growth Chemical inhibition of algae may occur through substances released by other organisms	Harnesses power of natural biological interactions May provide responsive and prolonged control	Some algal forms appear resistant Use of plants may lead to problems with vascular plants Use of plant material may cause depression of oxygen levels	Not applicable (see below for discussion of alternatives)
20a) Plantings for nutrient control	Plant growths of sufficient density may limit algal access to nutrients Plants can exude allelopathic substances which inhibit algal growth Portable plant "pods", floating islands, or other structures can be installed	Productivity and associated habitat value can remain high without algal blooms Can be managed to limit interference with recreation and provide habitat Wetland cells in or adjacent to the lake can minimize nutrient inputs	Vascular plants may achieve nuisance densities Vascular plant senescence may release nutrients and cause algal blooms The switch from algae to vascular plant domination of a lake may cause unexpected or undesirable changes Allelopathic effect on cyanobacteria depends on plant species (Pakdel et al., 2013)	Not applicable Much of the lake is too deep to support vascular plants Relatively few locations for wetlands May result in vascular plant increase lake wide
20b) Plantings for light control	Plant species with floating leaves can shade out many algal growths at elevated densities	Vascular plants can be more easily harvested than most algae Many floating species provide waterfowl food	Floating plants can be a recreational nuisance Low surface mixing and atmospheric contact promote anoxia	Not applicable Lake too deep Plants would interfere with recreational activities

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY TO LAKE KANASATKA
20c) Addition of barley straw	Input of barley straw can set off a series of chemical reactions which limit algal growth Release of allelopathic chemicals can kill algae Release of humic substances can bind phosphorus	Materials and application are relatively inexpensive Decline in algal abundance is more gradual than with algaecides, limiting oxygen demand and the release of cell contents	Success appears linked to uncertain and potentially uncontrollable water chemistry factors Depression of oxygen levels may result Water chemistry may be altered in other ways unsuitable for non-target organisms	Not applicable Lake too large Experimental technique with unpredictable results Adding additional carbon may further deplete dissolved oxygen
20d) Floating Wetlands	Planting artificial islands with emergent plants to absorb nutrients and support microbial communities in the roots Removal of plants after growing season	Decreases nutrients in the epilimnion Permanently removes nutrients from the lake if macrophytes are harvested after the growing season	Macrophyte senescence can lead to additional nutrient release and dissolved oxygen depletion in bottom waters Cyanobacteria blooms may occur despite low epilimnion phosphorus because they can regulate buoyancy to uptake P from other depth zones with higher P concentrations	Not applicable Lake has low epilimnion TP and high hypolimnion TP Limited data to support methods
21) Acidification	Disrupts cyanobacteria's ability to regulate buoyancy and maintain cell wall Lowering the pH out of the optimal growing range for cyanobacteria	May prevent resuspension of sediment-P from cyanobacteria movement May prevent nuisance algal blooms when immediate input reduction is not possible	Artificially lowering pH may impact the cell walls of other phytoplankton or harm other biota Lower pH conditions are favorable for release of P in sediments with certain Fe-P:Ca-P ratios (Huang et al., 2005) Some lakes are in recovery from the impacts of acid rain Does not address actual sources of algal nutrition Limited field data to support methods	Not applicable Whole-lake response: may severely impact other photosynthesizers and biota Fe-P:Ca-P ratio unknown Experimental technique with unpredictable results

Table B1 Citations

Bormans, M., Marsalek, B., & Jancula, D. (2015). Controlling internal phosphorus loading in lakes by physical methods to reduce cyanobacterial blooms: a review. Aquatic Ecology, 50(3), 407-422.

Carmignani, J.R., & Roy, A.H. (2017). Ecological impacts of winter water level drawdowns on lake littoral zones: a review. Aquatic Sciences, 79, 803-824.

DK Water Resource Consulting LLC & Water Resource Services, Inc. (DKWRC-WRS). (2020). Nippo Lake Internal Loading Treatment Plan; Barrington, NH. Appendix A.

D'ors, A., Sánchez-Fortún, A., Cortés-Téllez, A.A., Fajardo, C., Mengs, C., Nande, M., Martín, C., Costa, G., Martín, M., Bartolomé, M.C., & Sánchez-Fortún, S. (2023) Adverse effects of iron-based nanoparticles on freshwater phytoplankton Scenedesmus armatus and Microcystis aeruginosa strains. Chemosphere, 339, 139710.

Gächter, R., & Müller, B. (2003). Why the phosphorus retention of lakes does not necessarily depend on the oxygen supply to their sediment surface. Limnology and Oceanography, 48(2), 929-933.

Gächter, R., & Wehrli, B. (1998). Ten Years of Artificial Mixing and Oxygenation: No effect on the Internal Phosphorus Loading of Two Eutrophic Lakes. Environmental Science & Technology, 32, 3659-3665.

Gobler, C.J., Burkholder, J.M., Davis, T.W., Harke, M.J., Johengen, T., Stow, C.A., & Van de Waal, D.B. (2016). The dual role of nitrogen supply in controlling the growth and toxicitiy of cyanobacterial blooms. Harmful Algae, 54, 87-97.

Herman, B.D., Eberly, J.O., Jung, C.M., & Medina, V.F. (2017). Review and Evaluation of Reservoir Management Strategies for Harmful Algal Blooms. U.S. Army Corps of Enginners: Engineer Research and Development Center, ERDC/EL TR-17-11.

Huang, Q., Wang, Z., Wang, C., Wang, S., J, X. (2005). Phosphorus release in response to pH variation in the lake sediments with different ratios of iron-bound P to calcium-bound P. Chemical Speciation and Bioavailability, 17(2), 55-61.

Huser, B.J., Egemose, S., Harper, H., Hupfer, M., Jensen, H., Pilgrim, K.M., Reitzel, K., Rydin, E., Futter, M. 2016. Longevity and effectiveness of aluminum addition to reduce sediment phosphorus release and restore lake water quality. Water Res. 97:122–132.

Kasprzak, P., Benndorf, J., Gonsiorczyk, T., Koschel, R., Krienitz, L., Mehner, T., Hülsmann, S., Shultz, H., & Wagner, A. (2007). Reduction of nutrient loading and biomanipulation as tools in water quality management: Long-term observations on Bautzen Reservoir and Feldberger Haussee (Germany). Lake and Reservoir Management, 23(4), 410-427.

Li, Q., & Shi, W. (2020). Effects of sediment oxidation on phosphorus transformation in three large shallow eutrophic lakes in China. Environmental Science and Pollution Research, 27, 25925-25932.

Liu, X., Tao, Y., Zhou, K., Zhang, Q., Chen, G., & Zhang, X. (2017). Effect of water quality improvement on the remediation of river sediment due to the addition of calcium nitrate. Science of the Total Environment, 575, 887-894.

Pakdel, F.M., Sim, L., Beardall, J., Davis, J. (2013). Allelopathic inhibition of microalgae by the freshwater stonewort, Chara australis, and a submerged angiosperm, Potamogeton crisupus. Aquatic Botany, 110, 24-30.

Preece, E.P., Moore, B.C., Skinner, M.M., Child, A., & Dent, S. (2019). A review of the biological and chemical effects of hypolimnetic oxygenation. Lake and Reservoir Management, 35(3), 229-246.

Riza, M., Ehsan, M.N., Pervez, M.N., Khyum, M.M.O., Cai, Y., & Naddeo, V. (2023). Control of eutrophication in aquatic ecosystems by sustainable dredging: Effectiveness, environmental impacts, and implications. Case Studies in Chemical and Environmental Engineering, 7, 100297.

Romo, S., Soria, J., Fernández, F., Ouahid, Y., & Barón-Solá, A. (2013). Water residence time and the dynamics of toxic cyanobacteria. Freshwater Biology, 58, 513-522.

Shantz, M., Dowsett, E., Canham, E., Tavernier, G., Stone, M., & Price, J. (2004). The effect of drawdown on suspended solids and phosphorus export from Columbia Lake , Waterloo, Canada. Hydrological Processes, 18, 865-878.

Søndergaard, M., Liboriussen, L., Pedersen, A.R., & Jeppesen, E. (2008). Lake restoration by Fish Removal: Short- and Long-Term Effects in 36 Danish Lakes. Ecosystems, 11, 1291-1305.

Visser, P. M., Ibelings, B.W., Bormans, M., & Huisman, J. (2015). Artificial mixing to control cyanobacterial blooms: a review. Aquatic Ecology, 50, 423-441.

Willenbring, P.R., Miller, M.S., & Weidenbacher, W.D. (1984). Reducing Sediment Phosphorus Release Rates in Long Lake Through the Use of Calcium Nitrate. Lake and Reservoir Management, 1(1), 118-121.