Memo

To:	Paul Swanson District Manager Pine Soil & Water Conservation District 1610 Highway 23 North Sandstone, MN 55072	From:	Dendy Lofton, PhD, CLM Tom Beneke Adrianna Gorsky, PhD Plymouth, MN
Project/File:	227708083	Date:	February 18, 2026
CC:	Rachel Wheeler, Cross Lake Association		

Reference: Cross Lake Internal Loading and Alum Feasibility Study

Overview

In 2010, Cross Lake was listed on the Minnesota Pollution Control Agency's (MPCA) impaired water list due to excessive phosphorus (P). In response, the Snake River Watershed Total Daily Maximum Load[1] (Snake River TMDL) was developed in 2013 and provides Cross Lake's estimated P budget along with the associated load reductions required to meet state eutrophication standards.

Cross Lake has three primary basins: the South, Central and North Basins. As noted in the TMDL, the South Basin exhibits physical and limnological characteristics that are different than the Central and North Basins because of the hydraulic residence time. The South Basin is more strongly influenced hydrologically by the Snake River leading to a residence time of approximately 9 days and characterized as a widen reach of the river. In contrast, the Central and North Basins exhibit significantly longer residence times (0.8 to 1.5 years) and function as lake basins. The TMDL applies only to the Central and North Basins and does not apply to the South Basin. The Snake River TMDL found internal P loading was the largest source of P, accounting for 69% of the total P budget for the North and Central Basins.

Stantec Consulting Inc (Stantec) recently completed lake response modeling for Cross Lake to determine the magnitude of internal and external phosphorus loading. Stantec directly measured internal sediment P release, quantified the mass of mobile P in sediment, and assessed the spatial variability in sediment P concentrations across depth contours and vertically in the sediments. Lake response models can additionally be used to understand how in-lake P concentration responds to changes in nutrient loading. Based on sediment chemistry analyses and lake response modeling with reduced internal loading, Stantec determined the feasibility of an aluminum sulfate (alum) treatment, along with a cost-benefit analysis for Cross Lake. This technical memorandum describes the methods, results, and conclusions from the study.

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[1] Minnesota Pollution Control Agency, 2013. Snake River Watershed Total Maximum Daily Load Report.

Water Quality Data Summary

Historical profiles collected in 2010 and 2011 in each basin as part of the Snake River TMDL indicate that Cross Lake can experience stratification, resulting in differences in temperature and dissolved oxygen (DO) between surface and bottom waters. During stratified periods, the hypolimnion (bottom layer) can become anoxic, with DO concentrations at or below 2 mg/L. In 2010 and 2011, all three basins had anoxic bottom waters during either July or August sampling. Although Cross Lake is relatively deep, its long fetch promotes the development of a deeper thermocline, thereby restricting anoxic conditions to the deepest bottom waters.

More recently, Stantec conducted spatial sampling along a latitudinal transect in October 2025 (Figure 1). Bottom waters were anoxic at all sites except the shallowest location in the South Basin (Figure 2). These findings indicate that, even during periods of relative thermal mixing, anoxic conditions can persist near the sediment across all three basins, with important implications for internal lake processes.

Reference: **Cross Lake Internal Loading and Alum Feasibility Study**

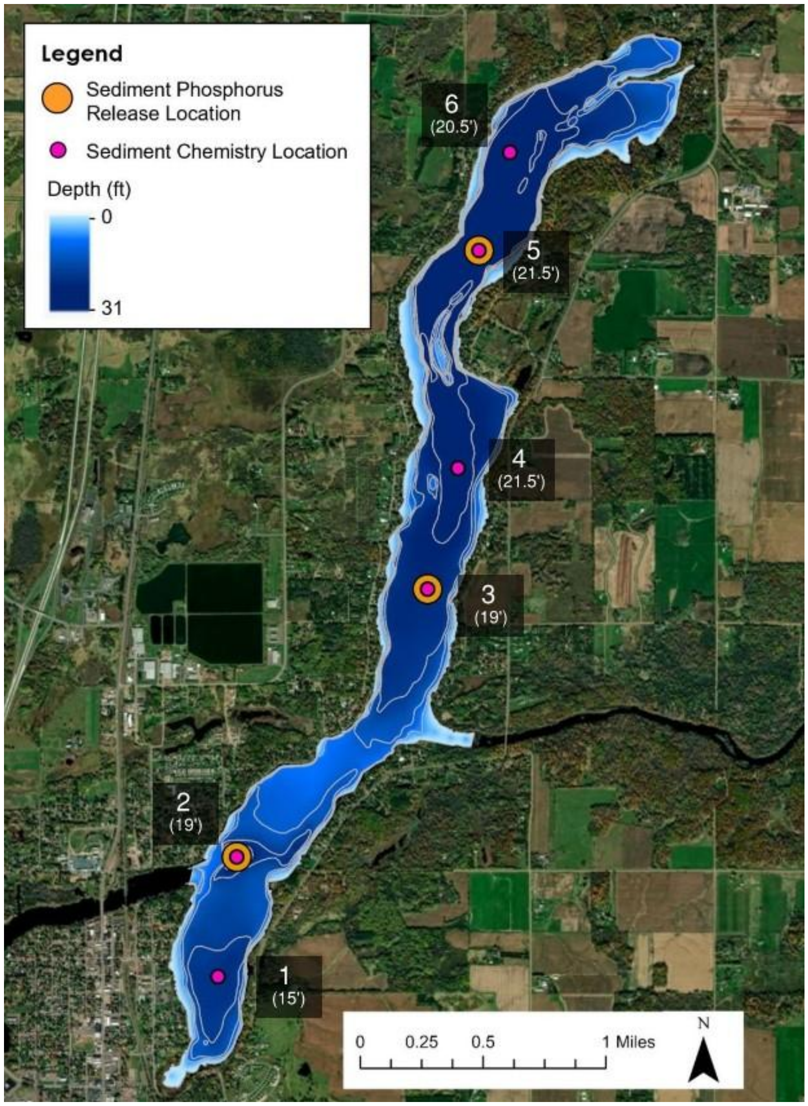

Figure 1. Map showing sampling locations and depths for dissolved oxygen and temperature profiles and sediment coring across the three basins in Cross Lake on October 13, 2025.

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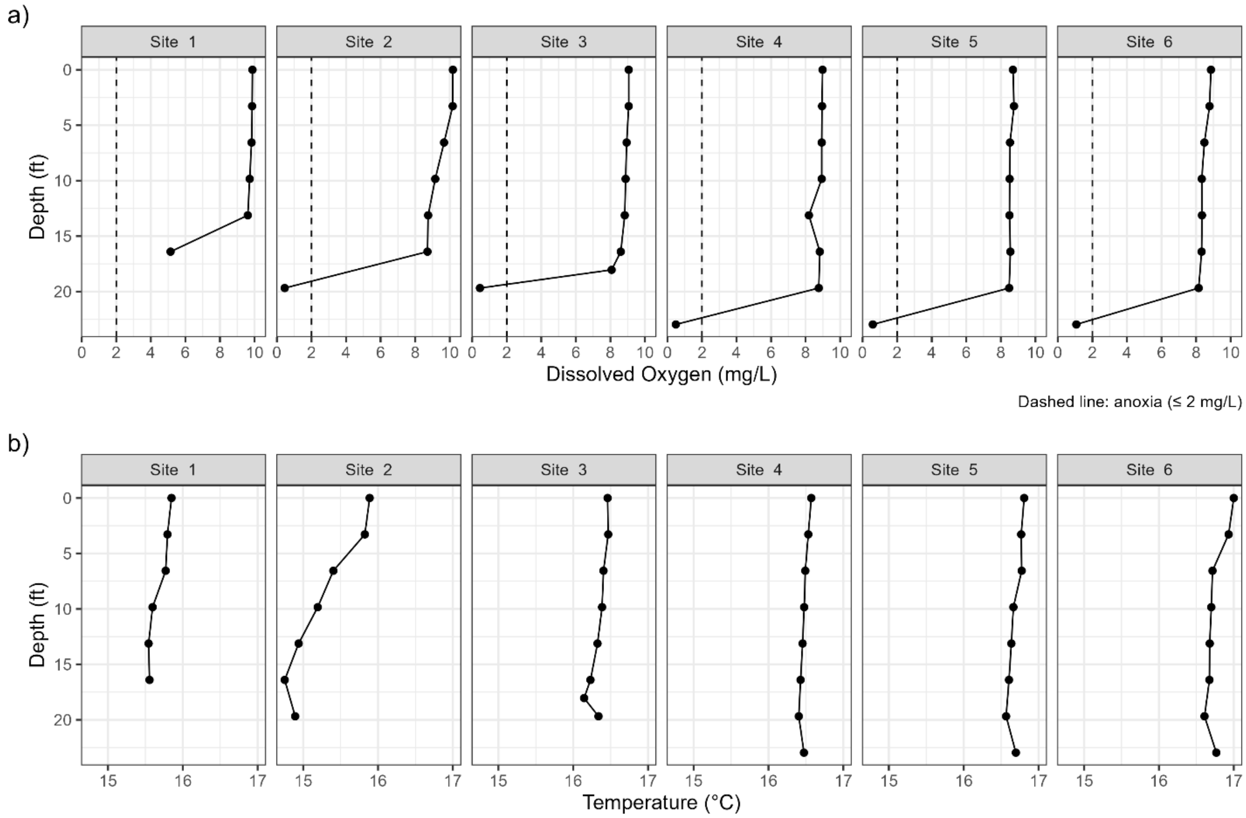

Figure 2. a) Dissolved oxygen and b) temperature profiles at the six sites on October 13, 2025.

Understanding the lake’s mixing and oxygen regime is critical for interpreting in-lake total phosphorus (TP) concentrations and informing lake response modeling. TP data were used to develop modeling assumptions and to help explain mechanistic lake processes that may not be fully captured by the model. Surface TP concentrations were obtained from AQuIA, based on monthly summer sampling (May-September) conducted in 2010 and 2011 (Table 1). Across the three basins, summer TP concentrations exceeded the 40 µg/L water quality criteria for deep lakes in the North Central Hardwood Forest Ecoregion (MN 7050.0222). Chlorophyll-a concentrations were also higher in the North and Central basins than the standard of 14 µg/L and Secchi was lower than the standard across the three basins.

Table 1. Mean eutrophication parameter values reported in the TMDL (2010-2011) and applicable standards for Cross Lake (North Central Hardwood Forest Ecoregion, NCHF)

Criteria or Average Concentration (2010-2011)	Total Phosphorus (µg/L)	Chlorophyll-a (µg/L)	Secchi Depth (meters)
NCHF Stratified Lakes	≤ 40	≤ 14	≥ 1.4
North Basin	68.5	18	1.10
Central Basin	71.5	16.5	1.04
South Basin	97.5	6.5	1.17

Summer surface water TP concentrations generally reflect the combined effects of external phosphorus loading and biological processes like algal uptake. Figure 3 shows a time series of summer surface and bottom TP concentrations for the South Basin in 2018. Variation between bottom and surface concentrations suggests that the lake experiences stratification, allowing phosphorus (P) to accumulate at the bottom from sediment release.

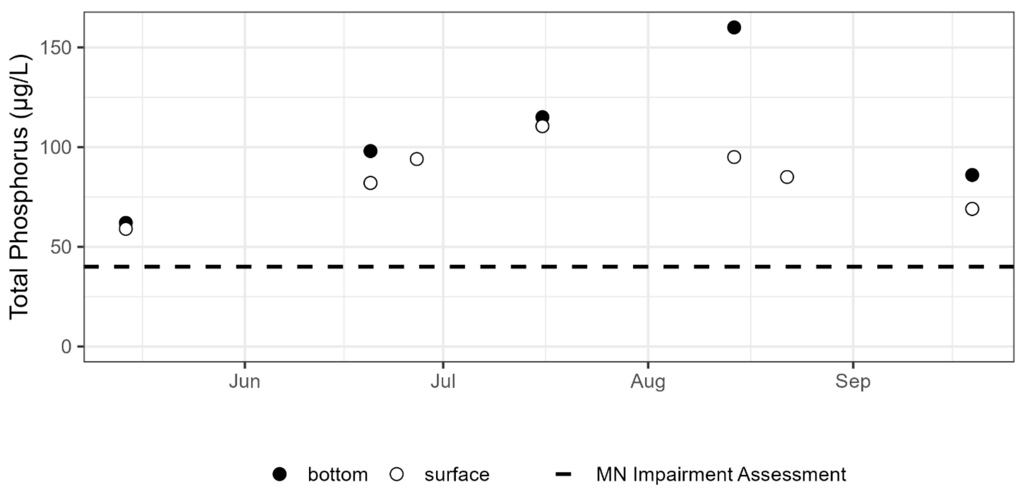

Figure 3. Surface (white) and bottom (black) total phosphorus (TP) concentrations from May-September 2018, with the eutrophication standard for deep lakes in the North Central Hardwood Forest Ecoregion represented as a dashed line.

Sediment Core Collection and Analysis

Sediment cores (n = 12) were collected from Cross Lake on October 13, 2025, across a range of depth contours along a latitudinal transect (Figure 1). Six of those sediment cores (one per site) were collected for P fractionation analysis, while an additional two cores were collected at sites 2, 3, and 5 to measure oxic and anoxic P flux. Sediments were collected using a gravity sediment coring device equipped with an acrylic core liner. Intact cores were hand delivered to University of Wisconsin-Stout (UW-Stout) for laboratory analysis.

In lake sediments, P exists in different chemical forms, which can be operationally classified as either mobile and subject to diffusion in a biologically available form or non-mobile, stable and unlikely to be released to overlying water to be consumed by algae (The combination of fractionation and flux measurements allows for a comprehensive assessment of sediment P dynamics. Fractionation quantifies the pools of P available for diffusion, while flux measurements quantify the rate of P release under anoxic and oxic conditions. Together, these data provide insight into spatial patterns of sediment P availability and potential release across different depth contours of the lake.

Sediment Phosphorus Chemistry

The laboratory-measured rates of sediment P release under anoxic conditions are shown in Figure 4 and oxic conditions in Figure 5. Anoxic sediment P release rates greater than 2 mg/m2/d are generally considered high and warrant evaluation of sediment treatment to mitigate internal loads as part of a holistic water quality improvement strategy. Anoxic sediment P release rates ranged from 13.59 to 20.19 mg/m2/day in Cross Lake, with an average of 16.5 mg/m2/day in the South Basin, 15.7 mg/m2/day in the Central Basin, and 16.9 mg/m2/day in the North Basin. All measured rates way exceeded the threshold of 2 mg/m2/d and were much higher than other deep lakes in Minnesota (n =12) indicating high sediment P release rates across the lake. Oxic release rates were generally low across sites, which is common.

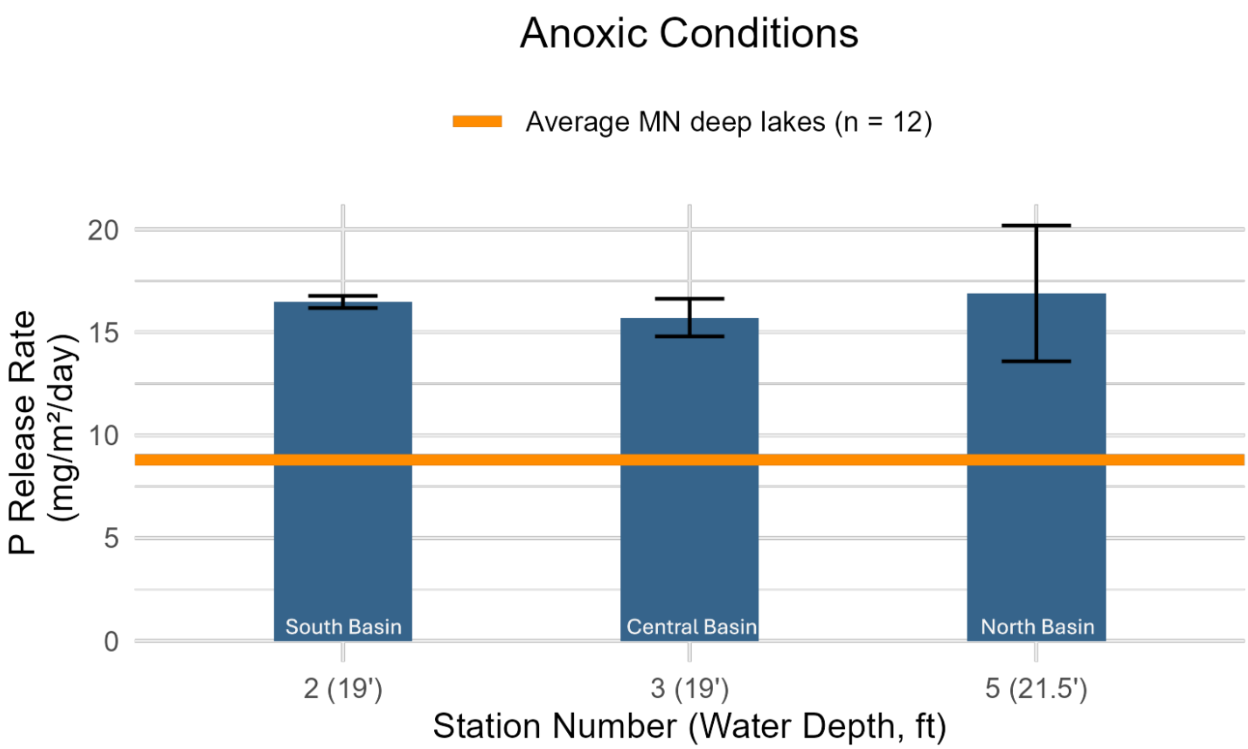

Figure 4. Laboratory-determined sediment phosphorus release rates under anoxic conditions across different water depths. Error bars indicate the standard error of the mean estimate. The orange horizontal line represents the average anoxic release rate for other deep lakes in Minnesota from our lake database (8.8 mg/m2/day).

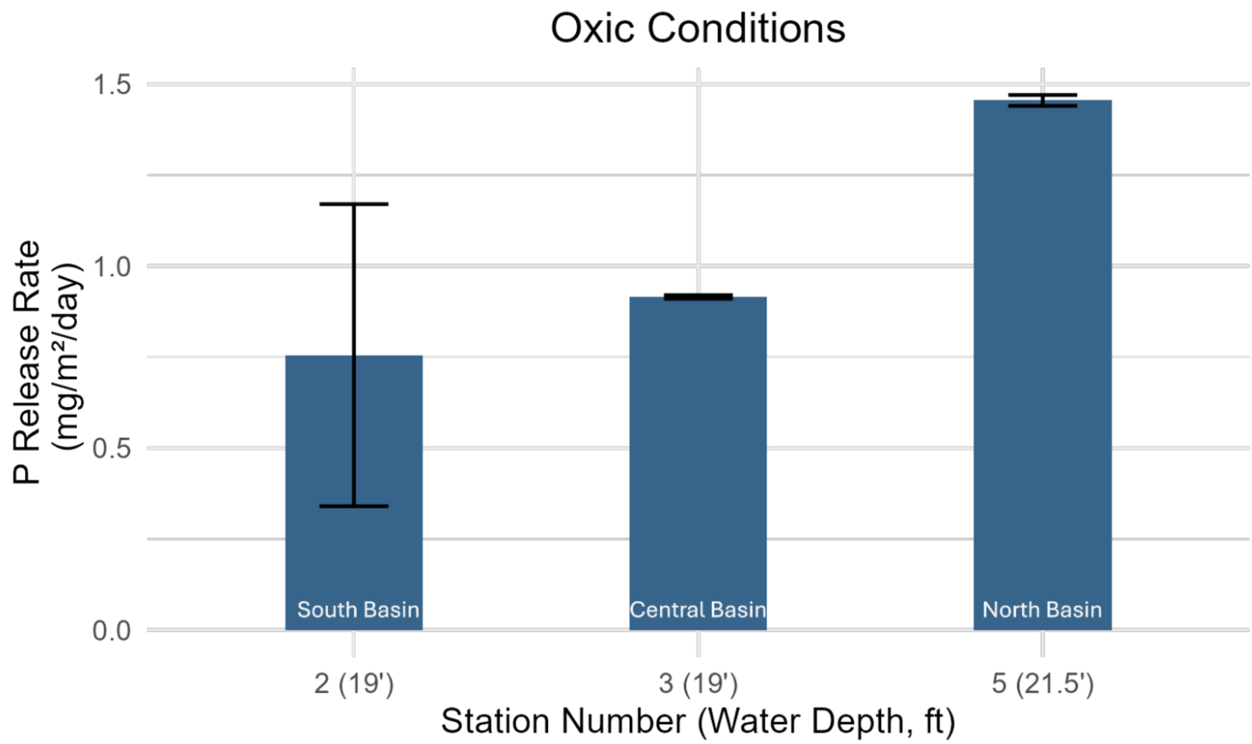

Figure 5. Laboratory-determined sediment phosphorus release rates under oxic conditions across different water depths. Error bars indicate the standard error of the mean estimate.

). The mobile fractions that most often drive P release under anoxic conditions are iron-bound P and loosely-bound P, collectively referred to as redox-sensitive P. Understanding the distribution of these fractions is critical for interpreting the potential for sediment P release and its role in lake nutrient dynamics.

Table 2. Operational grouping and recycling potential of phosphorus (P) fractions in lake sediments.

Operational Grouping	P Fraction	Recycling Potential
Mobile P pool	Iron-bound P	Biologically labile and may be recycled through biogeochemical and geochemical reactions.
	Loosely-bound P	
	Labile organic P	
Non-mobile P pool	Aluminum-bound P	Biologically refractory and subject to burial; not readily available for biological uptake.

At UW-Stout, sediment cores were processed for both P fractionation and P flux analysis. For fractionation, cores were sliced into discrete vertical sections (0-5 cm and 5-10 cm) to capture the vertical variability in P pools. In many lakes, mobile P concentrations are highest in the upper sediment layers, often decreasing around 4-6 cm. In rare cases, the vertical profile can show higher concentrations deeper in the sediments depending on lake dynamics and history of loading from the watershed.

For P flux measurements, duplicate cores were incubated under controlled temperature and light conditions to quantify the rate of sediment P release under oxic and anoxic conditions. The average of the two duplicates was used as the representative flux for each site.

The combination of fractionation and flux measurements allows for a comprehensive assessment of sediment P dynamics. Fractionation quantifies the pools of P available for diffusion, while flux measurements quantify the rate of P release under anoxic and oxic conditions. Together, these data provide insight into spatial patterns of sediment P availability and potential release across different depth contours of the lake.

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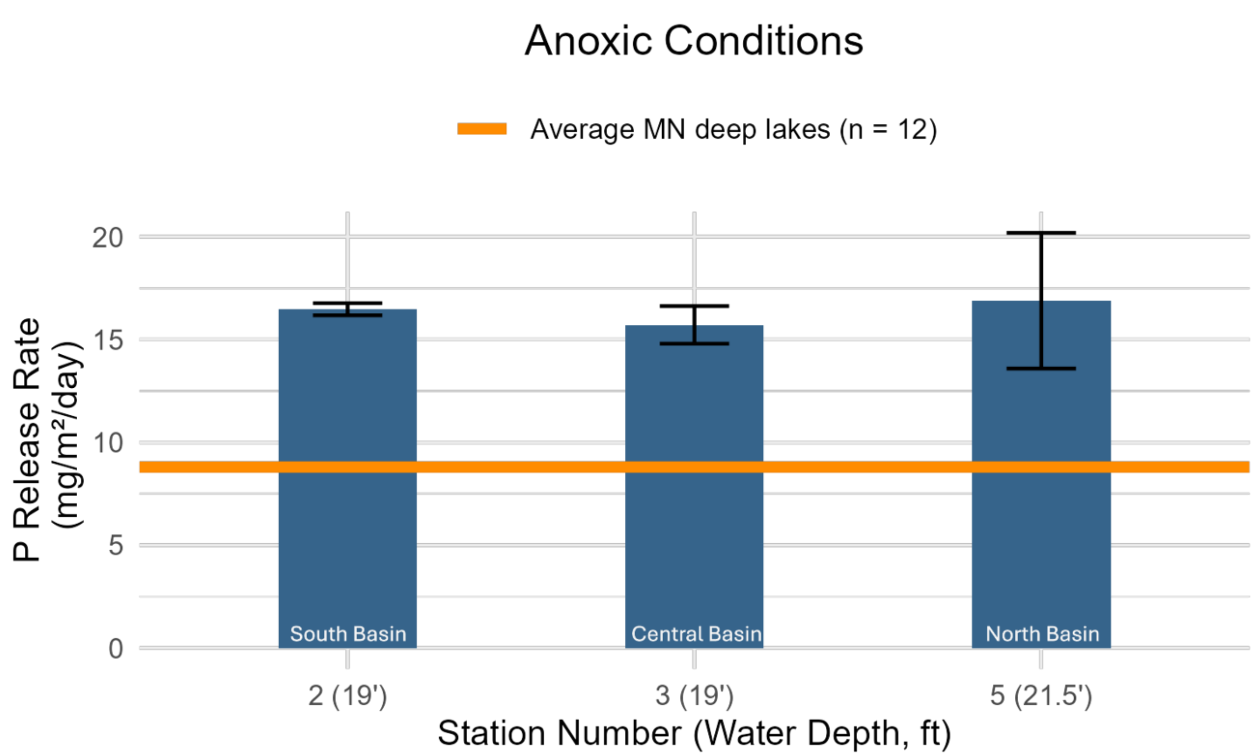

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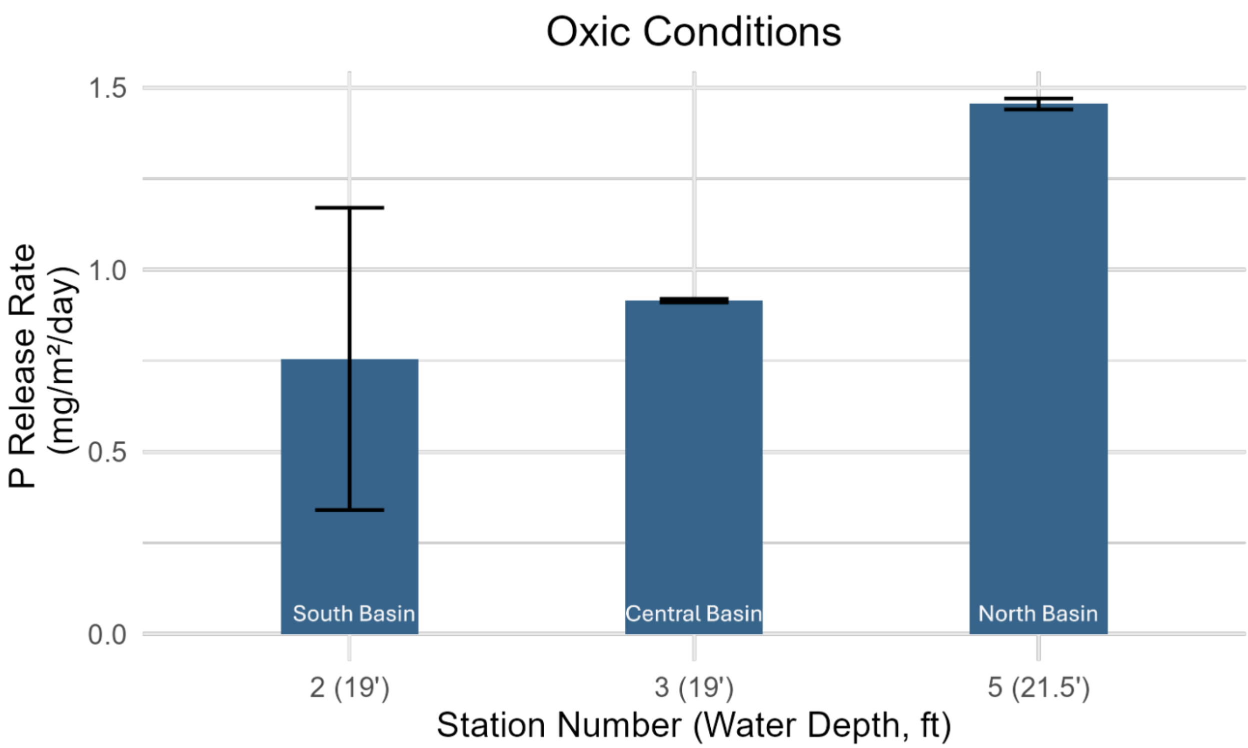

Figure 5. Laboratory-determined sediment phosphorus release rates under oxic conditions across different water depths. Error bars indicate the standard error of the mean estimate.

Sediment concentrations of redox-P are shown in Figure 6. This is the pool of P most likely to diffuse from sediments. The magnitude and spatial variability of these fractions is a key determinant in selecting the most effective treatment area for alum. The upper 0-5 cm sediment depth is a very active area of microbially-driven biogeochemical activity, which includes reduction of iron. When the bond between P and iron breaks, P gets diffused from the sediments into the overlying water column. Redox-P concentrations from all measured sites were well above the average concentration (0.49 mg/g) in our Minnesota lakes database (n = 12 deep lakes). Figure 7 shows the same information but includes the concentrations from the 5-10 cm sediment depth interval. Overall, across sites, the redox-P concentration was higher in the upper 0-5 cm portion compared to the 5-10 cm depth interval, which suggests that treating the 0-5 cm depth with alum will substantially reduce the potential for sediment P release from treated areas.

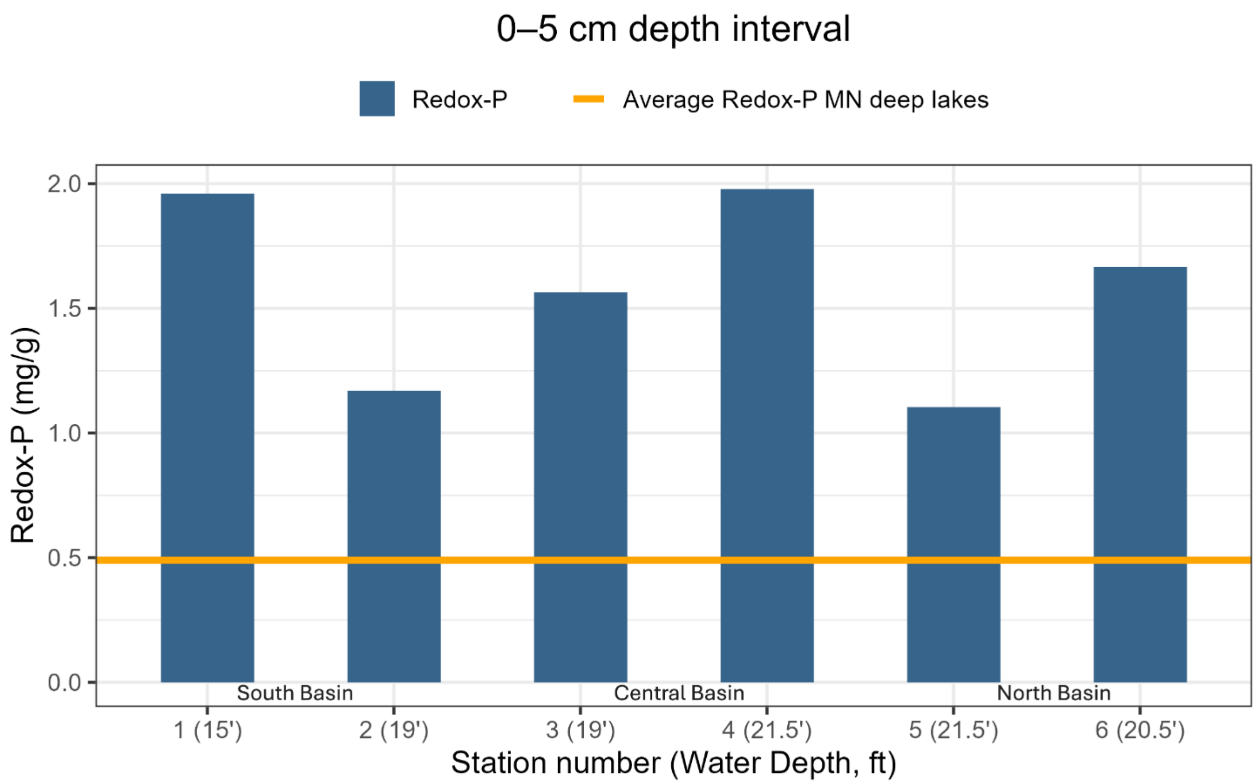

Figure 6. Redox-P concentrations in the upper 0-5 cm sediment depth interval across depth contours. The orange horizontal line represents the average redox-P concentration of 0.49 mg/g in the upper 0-5 cm sediment depth interval for other deep lakes in Minnesota from our database (n = 12).

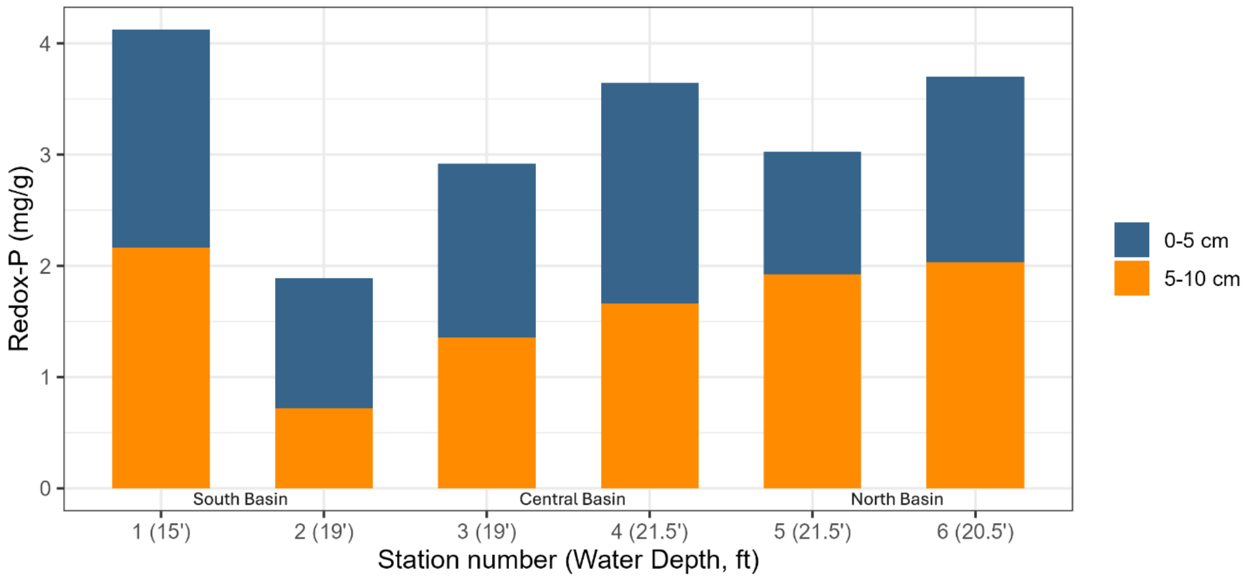

Figure 7. Redox-P concentrations in the upper 0-5 cm (blue) and the 5-10 cm (orange) depth interval across depth contours.

Compared to the 2012 data used in the Snake River TMDL, 2025 conditions show slightly lower anoxic diffusive P fluxes, except for at the Central Basin where there is a notable reduction. Iron-bound P concentrations were higher in 2025 compared to the Snake River TMDL in the North and Central Basins, but lower in the South Basin. Labile organic P was higher in 2025 compared to the TMDL data across all basins with the South Basin showing the smallest deviation between data years. The hydraulic residence time is much longer in the North and Central Basins compared to the South Basins, so these differences likely are a function of longer periods of time for phosphorus and organic matter to settle to the sediments from the overlying water column.

Table 3. Comparison of sediment P release rates and sediment chemistry with the 2012 results used to develop the Snake River TMDL[1]**.**

Sediment Core Location	Scenario	Anoxic Flux ($mg/m^2/day$)	Oxic Flux ($mg/m^2/day$)	Loosely-bound P (mg/g)	Iron-bound P (mg/g)	Labile Organic P (mg/g)
North	TMDL	17.8	0.5	0.029	0.395	0.116
	2025	16.9	1.5	0.059	1.454	0.209
Central	TMDL	31.1	1.8	0.077	0.952	0.147
	2025	15.7	0.9	0.024	1.437	0.310
South	TMDL	18.8	-	0.105	1.069	0.068
	2025	16.5	0.8	0.028	0.917	0.107

*2025 represents the average of 0-5 and 5-10 cm depth intervals, while the TMDL cores were analyzed at 0-10 cm.

Lake Response Model

Stantec updated the Snake River TMDL (2013) lake response models with 2025 laboratory-derived sediment P release rates. All other model inputs, such as anoxic factors for calculating internal loading, morphometric characteristics, and external P loading estimates remained the same as the original models (Table 4). We focused on the North and Central basins only, as the South Basin has such a short residence time that an alum treatment would not be recommended.

Table 4. Morphometric and anoxic factor inputs for North and Central basins from Snake River TMDL (2013).

Basin	Surface area (acres)	Volume (acre-ft)	Mean depth (ft)	Anoxic factor* (days)
North	344	5398	15.7	50
Central	269	4171	15.5	51

*The number of days where the anoxic sediment area is equal to the lake surface area.

The Canfield-Bachmann equation "models" in-lake TP concentrations based on an empirically derived regression analysis of lake data for lakes in North America[2]. Instead of using the natural lakes equation as done in the Snake River TMDL, Stantec used the equation for artificial lakes, which is summarized below:

$$P = \frac{L}{z(.114(L/z)^{0.589} + p)}$$

Each of the model (equation) variables are listed in Table 5. The resulting value, *P*, is used for comparison with the observed in-lake mean concentration. The fit of observed versus simulated concentration is used as a performance benchmark for verifying the accuracy and completeness of model inputs.

Table 5. Canfield-Bachmann equation variables for artificial lakes.

Variable Name	Variable Description
P	Predicted mixed layer TP concentration (µg/L)
L	Areal TP load (mg/m^2-yr)
z	Mean lake depth (m)
p	Flushing rate (yr^{-1})

Cross Lake met the conditional model constraints of applying Canfield-Bachmann equation for artificial lakes, which are shown in Table 6.

Table 6. Acceptable ranges for lake response model variables.

Lake or Tributary	Canfield-Bachmann
P	6-1,500 mg/m^3
L	40-820,000 mg/m^2/yr
z	0.6-59 m
p	0.019-1,800 yr

Other Model Inputs & Assumptions

External phosphorus sources to both basins of Cross Lake were explicitly characterized as model inputs for the Canfield-Bachmann model (Attachment A). Estimates of watershed (i.e., direct drainage) loading, failing septic systems, wastewater treatment facilities, and atmospheric loading were taken from the Snake River TMDL (2013). The general flow pattern in Cross Lake is from the North Basin to the Central Basin and ultimately to the lake outlet located between the Central and South Basins. Therefore, explicit flow and P loading were included from the North to Central Basin, along with a diffusive flux and associated load from the South Basin to both the North and Central Basins.

Internal P load was estimated by combining the laboratory-measured P release rates, outlined above, with the estimated number of anoxic days reported in the Snake River TMDL. Stantec assumed that oxic release

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[2] Canfield, D.E., and R.W. Bachmann, 1981, Prediction of total phosphorus concentrations, chlorophyll *a*, and Secchi depths in natural and artificial lakes: Canadian Journal of Fisheries and Aquatic Sciences, v. 38, no. 4, p. 414-423.

rates applied during periods when the anoxic sediment area was less than the total lake surface area. For each basin, the number of oxic days was multiplied by the basin surface area and the oxic release rate and then summed with the product of anoxic factor, basin surface area, and the anoxic release rate. This approach was used to estimate an annual internal phosphorus load (lbs/year) for each basin.

To simulate in-lake impacts of an alum treatment, internal P loads in the lake response models were reduced by an assumed 80% from the current estimated internal load in each basin. To estimate down-basin benefit of internal load reductions in North Basin, modeled changes in North Basin TP concentrations were translated into a proportional reduction in the North Basin's total annual P budget and exported load. That proportional reduction was then applied to the P load transferred from the North Basin to the Central Basin.

Lake Response Model Results

The results of the lake response models are shown in Table 7. The comparison between the observed TP concentration reported in the TMDL and the modeled TP concentration provides evidence of 1) how well inputs to the models are characterized and (2) how well the model equations fit the characteristics of Cross Lake.

Table 7. Lake response model results.

Basin	Observed TP (µg/L)	Modeled TP (µg/L)	Alum treatment in both basins TP (µg/L)	Alum treatment north basin only TP (µg/L)
North	68.5	83.4	51.6	51.6
Central	71.5	88.6	64.3	85.1

Both models overestimate average annual TP concentrations in the respective basins of Cross Lake by approximately 20%. In the absence of more recent monitoring data, we assumed that observed summer mean TP concentrations from 2010-2011 are representative of current conditions. The only updated input to the models is the internal load estimate, which is based on the release rates measured from sediment cores collected in 2025. Although the modeled TP concentrations are elevated, they remain within the range of TP concentrations observed in both basins during the June 1-September 30 monitoring period in 2010-2011, when maximum concentrations of 126 µg/L in the North Basin and 125 µg/L in the Central Basin were recorded.

Figure 8 and Figure 9 below characterize pollutant sources by their relative contributions to the North and Central basins. The primary inputs and outputs of the lake response models are summarized in Attachment A. A key objective of the modeling effort was to evaluate the relative magnitude of internal P release from sediments compared to other external sources of P to the lake. Internal loading accounted for approximately 75% of the total P load in the North Basin and 46% in the Central Basin, whereas direct drainage from the watershed contributed 22% of the total load to each basin.

Lake response models were also updated to include estimated TP load reductions and associated water quality improvements resulting from alum treatment. Assuming an 80% reduction in internal loading due to alum application, modeled TP concentrations in the North Basin decreased from 83.4 to 51.6 µg/L. Under this scenario, alum treatment is estimated to reduce the total annual TP load in the North Basin by ~59.8%, resulting in reduced TP export to the Central Basin. Based on the Canfield-Bachmann model, this reduction would decrease TP concentrations in the Central Basin from 88.6 to 85.1 µg/L. If both the North and Central basins received alum treatment, TP concentrations in the Central Basin would decrease from 88.6 to approximately 64.3 µg/L, according to modeled predictions.

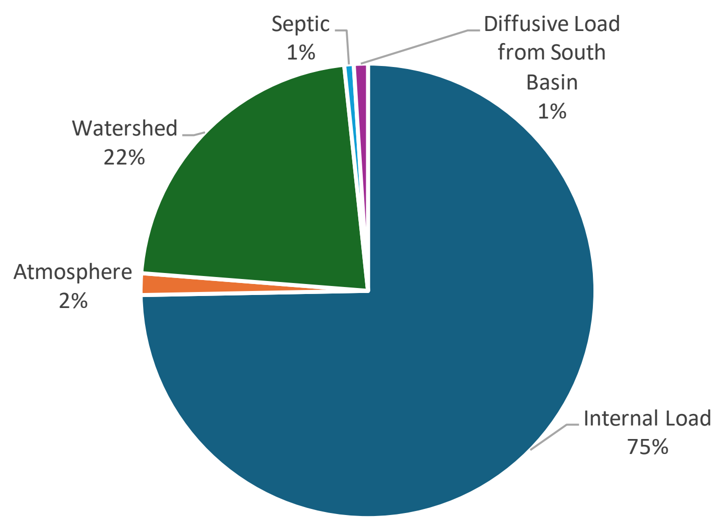

Figure 8. North Basin total phosphorus budget. Annual percent contribution by source as estimated in the lake response model.

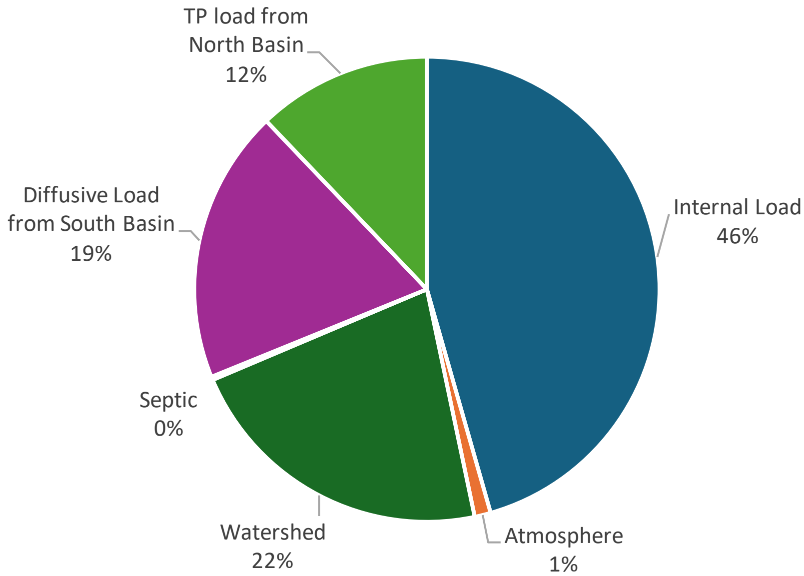

Figure 9. Central Basin total phosphorus budget. Annual percent contribution by source as estimated in the lake response model.

Alum Treatment Feasibility

Alum is one of the most common chemicals used for sediment P inactivation as the absorption of P to aluminum is very stable under environmental conditions and provides a long-term sink of P in the lake. Alum is applied to lakes by injection of liquid aluminum sulfate (with a chemical buffer in some cases) just below the lake water surface using a GIS-guided boat. Once injected in the water, the alum quickly forms a solid precipitate (floc) and settles to the bottom of the lake, typically within 24 hours of application. While the floc settles, it binds with dissolved P in the water column forming aluminum-bound P, which settles to the surficial sediments with the floc. Once the floc integrates into the surficial sediment matrix, it binds with dissolved P that is mobilized through geochemical and biogeochemical processes and converts it to a non-mobile P fraction (aluminum bound-P). The treatment reduces sediment P release rates and ultimately reduces internal P loading in lakes.

Three main factors are considered when determining whether to treat a lake with alum:

1) the rate at which phosphorus is released from the sediment under anoxic conditions,

2) the water depth and area of lake experiencing anoxia, and

3) the concentration of mobile-P fractions in the lake’s sediments.

The lab-measured sediment P release rates confirm anoxic release is elevated in Cross Lake at water depths 19 ft or greater. The most recent DO profiles taken in October 2025 show depths closest to the sediment-water interface do experience anoxic conditions even in the fall when the water column is thermally mixed. The sediment P chemistry data show that mobile-P concentrations are quite elevated in the 0-5 cm and 5-10 cm depth intervals. Together, these data indicate a strong potential for continued sediment P release under anoxic conditions that may persist for some time. Based on this information, Stantec recommends that an alum treatment be pursued in Cross Lake to reduce internal sediment loading coupled with watershed P reduction efforts to meet water quality criteria. Alum treatments typically assume a treatment depth of 4-6 cm in the dosing calculations. Targeting mobile-P concentrations below this typical treatment depth may require additional treatments over time to achieve the desired P load reduction.

During an alum application, pH must be maintained in the optimal range of 6.0-9.0 to (1) avoid toxicity due to persistence of free aluminum (which occurs at pH less than 6), (2) support completion of the hydrolysis reactions when applied to water, and (3) ensure that conditions are maintained that optimize aluminum-P binding. Alum is a weak acid, so large amounts of alum applied during one application have the potential to drive pH below 6, causing aquatic toxicity concerns. To better understand the likelihood of alum causing significant drops in pH in Cross Lake, UW-Stout measured the alkalinity and conducted a maximum allowable alum dose test to assess the lake's buffering capacity against alum, which is a weak acid. The maximum allowable volumetric does of aluminum to Cross Lake, before causing pH to fall below the optimal threshold was 18.75 mg/L based on measured alkalinity of 133 mg/L (as $CaCO_3$).

There are two potential strategies for handling cases where the calculated effected alum dose is high and there are concerns over maintaining pH in the optimal range:

- Buffered alum applications (2:1 ratio of alum + sodium aluminate) help bolster the ambient alkalinity to reduce acidification and the associated toxicity risks.
- Splitting alum doses into multiple applications also minimizes this risk. A multiple dose approach also has the potential to increase the effectiveness and longevity of the alum application by increasing the time that fresh alum is exposed to the uppermost sediment layer containing high redox-P. This scenario is often most advantageous when high external P loading from the watershed persists.

Redox-P in the sediments was higher in this study compared to the TMDL study indicating that the mass of phosphorus is continuing to accumulate in the sediments. While P release rates in this study were comparable to those reported in the TMDL, except in the Central Basin where rates were lower; however, the rates remain very high and highlight the importance of mitigating internal P loading through an alum treatment for water quality improvement (Table 3).

Alum Treatment Scenarios Considered

A few notes on terminology to support the reader's interpretation of this technical memo:

- **Aluminum** is the element that binds with phosphorus in lake sediments. The mass of aluminum is the basis for dosing calculations. The materials that are applied to lakes contain aluminum and come in the form of liquid **aluminum sulfate** (the material commonly referred to as alum) and **sodium aluminate** (the **buffer** to mitigate impacts on pH).
- **Treatment** refers to the prescribed dose of aluminum, which may be split into several **applications** to achieve the desired dose over time.
- **Redox-P** is the predominate fraction in the mobile-P pool that is subject to release from the lake sediments under **anoxic** (void of oxygen) conditions.
- A buffered alum application will be needed in Cross Lake. Henceforth, "alum" refers to a buffered application of aluminum in Cross Lake.

The TMDL study determined that internal P loading from the Central and North Basins accounts for 69% of the total P load to these basins, which is a very high proportion. The TMDL determined that a 64% load reduction is required from internal P loading, which strongly indicates the need for an alum treatment to reduce P release from the sediments. As part of the lake response modeling exercise, we assessed the influence of an alum treatment to the North Basin only (Table 7), which did not demonstrate a measurable impact on water quality to the Central Basin. Consequently, based on the TMDL study results and required internal P load reductions, and data collected in this current study, we evaluated two spatial areas for an alum treatment both the Central and North Basins.

We evaluated two different alum application scenarios or options, which are described below. Material estimates and planning-level cost estimates for each scenario are shown in **Table *8***. Note that the sediment core locations selected for this study were the same as the TMDL study and did not include the 15-ft water depth. Thus, for Scenario 1, we assumed the same redox-P concentration in both scenarios. Both scenarios assume a 5-cm vertical treatment depth and an Al:Al-P binding ratio of 20:1. The cost estimates provided are based on best available unit prices for alum and the buffer (sodium aluminate) at the time of data analysis and memo development in early 2026. Alum and sodium aluminate are subject to market fluctuations, so the actual cost may differ from the planning-level cost estimates in **Table *8***:

- Scenario 1: Treat areas 15 ft and greater
- Scenario 2: Treat areas 20 ft and greater

Table 8. Material volume and cost estimates for the alum dosing scenarios considered in this study.

Scenario	Water Depth (ft)	Treatment Area (acres)	Mass of Aluminum Required (kg)	Volume of Alum (gal)	Volume of Buffer (gal)	Approximate Material Costs ($)	Approximate Applicator Fees	Estimated Total Cost ($)
1	≥ 15	415	274,403	548,806	274,403	3,995,308	25,000	4,020,308
2	≥ 20	204	135,866	271,733	135,867	1,978,215	20,000	1,998,215

Recommendation

Stantec recommends Scenario 2 for Cross Lake, which is a buffered alum treatment that should be split over three applications of equal doses over water depths ≥ 20 feet with each application separated by one year as shown in Table 9. Approximately one-year following the second application in Year 4, additional sediment cores should be collected to measure the progress of the alum treatments to lower the internal P release rates and adjust the alum dose or expand the treatment to the 15-ft depth contours, depending on the lake's response as determined by ongoing surface water monitoring each summer. The importance and practicality of following an adaptive management approach is described in more detail in the following section.

Table 9. Recommended alum treatment strategy (Scenario 2) split over three applications in six years.

Al Treatment Strategy	Mass of Al Per Application (kg)	Alum (gal)	Buffer (gal)	Al Dose (g/2)	Al Dose (mg/L)	Approx Material Costs ($)*	Approx Applicator Fees ($)	Approx Total Cost ($)
Application Year 1	45,289	90,578	45,289	54.7	24.4	659,405	20,000	679,405
Application Year 3	45,289	90,578	45,289	54.7	24.4	659,405	20,000	679,405
Sediment Coring Year 4								$20,000**
Application Year 5	45,289	90,578	45,289	54.7	24.4	659,405	20,000	679,405
Totals	**135,866**	**271,733**	**135,866**	**164**	**73.27**	**$1,978,215**	**60,000**	**2,058,215**

** Planning-level estimates based on 2025 costs. Subject to market fluctuations.*

***Assumes approximately $10,000 in lab fees and $10,000 in labor for data analysis, dose evaluation and reporting.*

The mass of redox-P is quite high in the sediments of the measured depth contours. These areas also exhibit sustained periods of anoxia resulting in high sediment phosphorus release. With the high mass of redox-P in the sediments underlying water ≥ 20 ft, it is likely that the 15 ft depth intervals also have high redox-P but these sediments were not measured directly. Additional sediment cores could be collected from the 15-ft water depth in both the Central and North Basins to refine the alum dose and treatment strategy, but the expanded sediment measurements could be incorporated over time with adaptive management of the treatment and the lake's response, which is further discussed below.

Given the high redox-P concentrations in the measured sediments in this study and the TMDL study, it is highly expected that additional treatments will be needed in 5-10 years following completion of the three applications prescribed with Scenario 2 and shown in Table 9. It is impractical to apply a large amount of alum at one time; concentrations this high in the sediments (horizontally across the Central and North Basins and vertically within the measured sediment cores) require multiple treatments over time to achieve water goals. Additional data collection will be needed to monitor the lake's response to treatment and determine the need for future applications to the areas representing ≥ 20 ft, but also to determine if expanding the alum treatment to areas covering 15-ft water depths will be needed to achieve the internal P load reductions required by the TMDL and thus meeting water quality criteria.

Adaptive Management

Adaptive lake management is a proactive process that involves consistent collection of data to evaluate success of implemented actions and determine the need to adjust or adapt management based on data. It is a widely accepted scientific process that will be critically important to follow for Cross Lake to achieve water quality standards. Figure 10 shows the general process of adaptive lake management where data collection is at the heart of the process. Data is needed to determine the lake's condition, evaluate appropriate management actions, monitor the success of an action and evaluate progress towards goal attainment, and adaptively manage the process based on site-specific data.

Reference: Cross Lake Internal Loading and Alum Feasibility Study

Figure 10. Adaptive lake management process.

Recent studies have demonstrated the importance of monitoring lake and sediment conditions along with multiple applications over time, which are critical for lakes with high sediment redox-P and internal P loading rates[3,4]. As described above, a high volume of alum will be needed to mitigate the high concentration of redox-P in the Central and North Basins. There is evidence that the binding sites of alum may decrease over time, which impacts the longevity of a single application and supports the basis for multiple applications to treat sediments with high redox-P[3]. Cedar Lake in Wisconsin, for example, has a prescribed adaptive management strategy of alum applications over 10-12 years beginning in 2017. Cedar Lake is monitored annually for a range of parameters to evaluate water quality improvement and adaptively manage alum applications over time.

We anticipate that water quality improvements will be realized in Cross Lake with implementation of Scenario 2. However, water quality monitoring pre-and post-treatment will be critically important for determining the lake's response to treatment and the need for additional treatments in the future.

Below is a summary of monitoring activities that should be implemented along with Scenario 2 to adaptively manage internal P loading in Cross Lake.

- Recent water column TP (epilimnion and hypolimnion) are lacking for Central and North Basins, so we highly recommend monitoring of total phosphorus and orthophosphate in the surface and bottom waters in both basins to establish recent pre-treatment baseline conditions. Establishing

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[3] UW-Stout. 2024. Cedar Lake, Wisconsin – Limnological response to alum treatment: 2023 interim report. https://cedarlakewi.org/wp-content/uploads/2024/04/Cedar-Lake-2023-Alum-Treatment-Report.pdf. Accessed on 10 February 2026.

[4] James, William F. 2025. Internal loading, sediment phosphorus dynamics, and limnological response during alum management of a shallow oxbow Wisconsin lake. *Lake and Reservoir Management* 41(4): 328-346.

baseline conditions will be critically important for measuring the lake's response to the alum treatments.

- In thermally stratified waters, orthophosphate will accumulate in the hypolimnion during periods of anoxic driven sediment phosphorus release. Reductions in the hypolimnetic concentration of orthophosphate and the rate of release over the summer growing season is a key indicator of the alum treatment's effectiveness. This monitoring will help guide the need and timing for additional applications in the future after completion of Scenario 2.
- This data should be collected monthly (June-Sept) prior to the first alum application and for a minimum of 5 years following the first treatment.

- Collection of dissolved oxygen (DO) and temperature profiles in the Central and North Basins at 15 ft and 20 ft water depths (at 1-meter intervals) is highly recommended.
- The sediment surface area underlying the water depths of ≥ 15 ft and ≥ 20 ft cover 415 acres and 204 acres, respectively, which increases the cost of an alum application significantly (Table 8). In Year 4 of the treatment strategy (Table 9), sediment cores should be collected from the treated area (≥ 20 ft water depth) and the 15-ft water depth contour to measure redox-P and rates of internal P release for comparison to pre-treatment conditions. This sediment data, in combination with the DO profiles and phosphorus data collected at the epilimnion and hypolimnion from the Central and North Basins, will guide decisions regarding a change in alum dose or expansion of the treatment area. Specifically, these data will provide the following:
  - Measure of treatment progress towards the required internal phosphorus load reduction specified in the TMDL and improvements on surface water quality TP, chlorophyll-a and Secchi depth measurements.
  - Determination of whether the alum treatment should be expanded to the areas covering the 15-ft depth contour based on the redox-P, the temporal extent of anoxic conditions in these areas, and the surface concentration of TP in the Central and North Basins.
  - Evaluate water quality trends for determining progress towards meeting water quality criteria and support delisting efforts in the future. The decision to delist Cross Lake from the impaired waters list will be based on the surface concentration of TP, chlorophyll-a and Secchi depth measurements[5].
    - Cross Lake Association should refer to the MPCA's Standard Operating Procedures for Lake Water Quality Sampling for details on how to collect water quality data[6]. Stantec is happy to discuss details and provide guidance on sampling methods, frequency and data requirements for delisting lakes from the impaired waters list as well[5].

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[5] https://www.pca.state.mn.us/air-water-land-climate/minnesotas-impaired-waters-list
[6] https://www.pca.state.mn.us/sites/default/files/wq-s1-16.pdf

Estimated Alum Longevity

Treatment longevity is an estimated measure of how long an alum treatment can be expected to bind with sediment phosphorus and is estimated from a combination of observed and simulated physical and chemical lake attributes. The longevity of an alum application is highly dependent upon the continued extent of loads from the watershed, treatment area, extent of anoxia, concentration of mobile-P vertically in the sediment, and treatment strategy. Any phosphorus that enters the lake and settles on top of the alum floc layer does not physically interact with the alum and thus does not form chemical bonds. Phosphorus that diffuses from sediments beneath the alum layer will physically come into contact with the alum binding sites and will form strong chemical bonds. Over time, the alum layer will migrate further downward into the sediments due to settling organic and inorganic material. Once the alum layer becomes buried beneath 5 cm in the vertical sediments, the alum is assumed to be less effective as the upper 5 cm of phosphorus-laden sediments are subject to mobilization and diffusion. Thus, a split dose over multiple years can increase the overall longevity of the treatment, however, this is incredibly difficult to predict given the multitude of factors controlling the lake's response. And as discussed above in the Recommendations section, we anticipate that multiple applications will likely be needed over time to the Central and North Basins due to the high concentration of redox-P in the sediments.

Stantec evaluated alum treatment longevity based on the estimated accumulation of phosphorus across the lake bottom, or the sedimentation rate. The sedimentation rate-based approach was estimated using a combination of (1) lake morphometry data (e.g., lake area, lake depth, etc.), (2) the estimated amount of total phosphorus each lake receives annually, and (3) the measured total phosphorus concentration in lakebed sediment. Because treatment longevity calculation is based on a complex and nuanced set of both observed and estimated values it is not intended to yield precise results. It does, however, illustrate the expected lifetime of alum application reasonably well based on simulated settling rates and estimated timeline for the alum layer to be buried below the 5 cm sediment depth interval. Table 10 provides a summary of the data used for the alum longevity calculation.

Table 10. Summary of parameters used to estimate alum treatment longevity.

Parameter	Value	Units
Lake Area	614	acres
Estimated Sediment TP Concentration (top 5 cm)	2.6	mg/g dw
Estimated Annual TP Delivery	4,475	lbs/yr

The sedimentation-based approach for estimating treatment longevity suggests that 5 cm of accumulation will occur over the lakebed after approximately 15.6 years based on external loading estimates from the approved TMDL. Thus, an alum treatment could be effective in Cross Lake for *up to* 15 years based on external P loading estimates.

Alum treatment longevity is inherently challenging to estimate and the phosphorus sedimentation approach has limitations. This approach does not estimate a treatment objective or in-lake response. Rather, it is a generalized method for evaluating the anticipated period in which the alum treatment would be actively binding phosphorus. The goal of this analysis is to simply assess whether a treatment will be quickly buried based on phosphorus settling. Consequently, longevity will depend on the lake's response to the prescribed alum dose strategy, the potential for areas underlying the 15-ft depth contour to experience anoxia and release of P from sediment, which has high concentrations of redox-P vertically down to 10-cm sediment depth. As discussed above, Cross Lake will likely see immediate improvements in water quality following the application strategy described here. Meeting the water quality standards and delisting the lake will require an adaptive management approach coupled with ongoing water quality data to measure progress and guide future applications of alum.

Summary

- This study confirms the TMDL assessment that internal P loading is high in the Central and North Basins and that an alum treatment is necessary to reduce that load in the ongoing effort to improve water quality in Cross Lake.
- Redox-P concentrations in the Central and North Basins are well above the average concentration found in our database of deep lakes based on data collected in the last five years. The concentrations are high horizontally across sediments in the 20-ft water depth and vertically downcore to 10 cm. These data indicate that a high mass of aluminum will be needed to mitigate internal P loading from lake sediments.
- A high dose of aluminum, and moderate alkalinity, indicates the need for a buffered alum treatment to be split into multiple applications over time. We recommend that one-third of the dose is applied in Year 1, one-third of the dose is applied in Year 3, and the remaining one-third dose in Year 5.
- Recent water quality data for the Central and North Basins is lacking and will need to be collected prior to an alum treatment and consistently following the first application to evaluate effectiveness of the treatment and progress towards water quality improvement. Stantec provided references to two documents from the MPCA to facilitate this process, and we are happy to support discussions and logistics in any way that we can.
- While we expect to see water quality improvement following implementation of Scenario 2 described above, the high redox-P concentrations in the sediments indicate that additional treatments may be needed in the future. Water quality monitoring of the surface waters and bottom waters of the Central and North Basin will guide the need for additional alum treatments through an effective adaptive management process by directly measuring the lake's response to treatment. In

Year 4, collection of sediment cores for phosphorus release rates under anoxic conditions can be compared to pre-treatment release rates. A significant reduction in sediment phosphorus release rates is anticipated.

- Below is a summary of the near-term next steps for the Cross Lake Association based on the results of this study to implement an alum treatment:
    - Procurement of funds and/or grants to support the alum treatment.
    - Development of bid documents and technical specifications for the alum treatment by a consultant along with bidding support to select a qualified alum applicator.
    - Selection of a qualified alum applicator and sign contracts for the alum application strategy.
    - Prior to the first alum application, collection of water quality data in the surface and bottom waters of the North and Central Basins to establish pre-treatment conditions for comparison to post-treatment conditions.

Attachment A- Lake Response Models

Cross Lake (North Basin) – Canfield-Bachmann Lake Response Model Equation Parameters

Category	Description	Value	Unit
Lake Attributes	Lake Area	344.0	acres
Lake Attributes	Average Depth	15.70	feet
Lake Attributes	Max Depth	27.0	feet
Lake Attributes	Volume	5,398	acre-feet
Internal Load	Anoxic Release Rate (2025 Cores)	16.89	$mg/m^2/day$
Internal Load	Oxic Release Rate (2025 Cores)	1.46	$mg/m^2/day$
Internal Load	Anoxic Factor	50.00	days
Internal Load	Anoxic Internal TP Load	2,592	lbs/year
Internal Load	Oxic Internal TP Load	1,407	lbs/year
Internal Load	Total Internal Load	3,998	lbs/year
Internal Load	Internal TP Load (Alum Scenario)	800	lbs/year
Atmospheric Load	Atmospheric TP Load	82.2	lbs/year
External Load	WWTFs	0	lbs/year
External Load	Failing Septic	36	lbs/year
External Load	Direct TP Load	1,218	lbs/year
External Load	"Net Diffusive Inflow" from South Basin	54	lbs/year
Total Load	Total Annual Discharge	3,729	acre-ft/year
Total Load	TP	5,353	lbs/year
Total Load	TP (Alum Scenario)	2,154	lbs/year
Model Equation – Base Conditions	L*	1744.0	$mg/m^2/year$
Model Equation – Base Conditions	p*	0.7	$year^{-1}$
Model Equation – Base Conditions	z*	4.785	m
Model Equation – Base Conditions	P* (Simulated TP Concentration)	83.4	µg/L
Model Equation – North Alum	L* (Alum Scenario)	701.8	$mg/m^2/year$
Model Equation – North Alum	P* (Simulated TP Concentration- Alum Scenario)	51.6	µg/L
Observed TP Concentration	Observed In-Lake TP Concentration	68.5	µg/L

Reference: **Cross Lake Internal Loading and Alum Feasibility Study**

Cross Lake (Central Basin) – Canfield-Bachmann Lake Response Model Equation Parameters

Category	Description	Value	Unit
Lake Attributes	Lake Area	269.0	acres
Lake Attributes	Average Depth	15.50	feet
Lake Attributes	Max Depth	22.0	feet
Lake Attributes	Volume	4,171	acre-feet
Internal Load	Oxic Internal TP Load (2025 Cores)	0.9	lbs/year
Internal Load	Anoxic Release Rate (2025 Cores)	15.72	$mg/m^2/day$
Internal Load	Anoxic Factor	51.00	days
Internal Load	Anoxic Internal TP Load	1,923	lbs/year
Internal Load	Oxic Internal TP Load	690	lbs/year
Internal Load	Total Internal TP Load	2,613	lbs/year
Internal Load	Internal TP Load (Alum Scenario)	523	lbs/year
Atmospheric Load	Atmospheric TP Load	64.4	lbs/year
External Load	WWTFs	0	lbs/year
External Load	Failing Septic	13	lbs/year
External Load	Direct TP Load	1,270	lbs/year
External Load	TP Load From North Basin	695	lbs/year
External Load	TP Load From North Basin Alum Treatment	280	lbs/year
External Load	"Net Diffusive Inflow" from South Basins	1,090	lbs/year
Total Load	Total Annual Discharge from North Basin	3,729	acre-ft/year
Total Load	Total Annual Discharge from Direct Drainage	1,459	acre-ft/year
Total Load	TP	5,733	lbs/year
Total Load	TP	5,317	lbs/year
Total Load	TP	3,227	lbs/year
Model Equation – Base Conditions	L*	2388.6	$mg/m^2/year$
Model Equation – Base Conditions	p*	1.2	$year^{-1}$
Model Equation – Base Conditions	z*	4.724	m
Model Equation – Base Conditions	P* (Simulated TP Concentration)	**88.6**	µg/L
Model Equation – North Alum	L*	2215.5	$mg/m^2/year$
Model Equation – North + Central Alum	L*	1344.5	$mg/m^2/year$
Model Equation – North Alum	P* (Simulated TP Concentration)	**85.1**	µg/L
Model Equation – North + Central Alum	P* (Simulated TP Concentration)	**64.3**	µg/L