Analysis of in situ internal phosphorus load: *Bone Lake, Polk County Wisconsin*

2015-2017

Data collected and analyzed by: Ecological Integrity Service, Amery WI with contribution from UW-Stout Center for Limnological Research and Rehabilitation, Menomonie WI and Harmony Environmental, Amery WI

Summary

In situ internal phosphorus loading was evaluated in Bone Lake, Polk County, Wisconsin from 2015 to 2017. Data from dissolved oxygen and temperature profiles were collected at 24 locations scattered throughout the potential anoxic area weekly from mid-May until the end of September each year. These sample sites were distributed between three separate basins within Bone Lake. Internal load was calculated by phosphorus accumulation in the hypolimnion during anoxia and stratification. The phosphorus release was also calculated using mean phosphorus concentration before and after full lake mixing in August.

Anoxia ranged from 60 days (2015) to 70 days (2016 and 2017) based upon area weighted means in the observed anoxic regions of the bottom sediment. The lake was stratified but weakly, especially in 2015 and 2016 compared to 2017. This suggests potential mixing between the hypolimnion and epilimnion throughout the summer. Each year had a full lake mix event in early to mid-August, resulting in substantial phosphorus release.

The mean internal loading of phosphorus from anoxic sediments calculated from hypolimnion accumulation ranged from 1570 to 1598 kg. The phosphorus release calculated from before and after full lake mixing in August ranged from 1544 to 1870 kg. The mean for all methods over the three year period, including sediment core release amounts (James, 2018) was 1594 kg. This accounted for 55% of the mean total phosphorus load. The epilimnion phosphorus trends showed probable mixing from weaker stratification in July to early August, followed by a substantial full lake mix and phosphorus release in early to mid-August.

The external load appears to be a significant contributor to the total load as well. In 2015, there were several intense rain events which appear to have increased the total load. In 2017, the precipitation amounts were lower and the lake phosphorus concentration was lower than in 2015. Assuming internal load was similar in both years, the difference in total load is likely due to runoff differences.

Background

Bone Lake is a 1704 acre lake[1] with a maximum depth of 44 feet and a mean depth of 23 feet. The lake is listed as having a eutrophic status (according to the Wisconsin Dept. of Natural resources) for total phosphorus, chlorophyll-a and secchi depth. In 2017 the Carlson Trophic Index reached 59 for total phosphorus, 61 for chlorophyll-*a* and 58 for secchi disk, all in the eutrophic category. Paleolimnological analysis conducted in 2015 suggests that Bone Lake has been eutrophic for many years, estimating total phosphorus reaching 0.062 to 0.080 mg/L based upon historical diatom species composition (Edlund et al, 2015). Furthermore, the algae blooms are typically dominated by cyanobacteria species (blue-green algae)(Edlund et al, 2017). There are two perennial tributaries that flow into Bone Lake, both from the west. One is unnamed (flows into northwest portion of lake) and the other is known as Prokop Creek. Bone Lake has extensive development in the riparian zone with many areas fully developed with buildings and lawns.

Internal loading through sediment release of phosphorus can increase productivity in lakes. Lakes with high summer phosphorus release from anoxic sediments can correlate with high chlorophyll concentrations (Nurnberg, 1998). If the lake is stratified, there is little mixing into the water column and the phosphorus will not be available during much of the growing season. In these cases, the phosphorus concentration in the epilimnion can be predicted from external loading alone (Nurnberg, 1998). However, if stratification is weak, mixing allows phosphorus to get integrated into the epiliminion from the hypoliminion due to the degradation of the thermocline. The epilimnion phosphorus concentration will increase during the growing season, available for algae production throughout the summer season. The earlier and more frequently this mixing occurs, the more phosphorus is available for productivity during the growing season. If a lake remains strongly stratified through most of the growing season, there can be a substantial phosphorus release but that phosphorus is not available during much of the growing season, thus not available for production of algae.

Release of phosphorus from anoxic sediments is dependent upon the area of anoxia, the anoxic period or duration, and the phosphorus release rate per lake area (typically square meters) (Nurnberg, 1995). Bone Lake has a history of anoxia in the near bottom, but the extent of the anoxia in both area and duration were unknown prior to this study.

The nutrient loading in Bone Lake has been modeled in years past, but there was concern over the external load being uncertain. This can tend to occur when there is a large internal load that has not been measured accurately due to lack of data. In addition, Bone Lake has had variable algae blooms and water clarity from year to year with little change in precipitation and no known major land use changes. These changes are potentially due to internal load with variable stratification and mixing within the lake in any given year. In previous modeling of Bone Lake, the Wisconsin Lakes Modeling Suite was used to determine the Osgood Index (Osgood, 1988). The Osgood

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[1] Lake area and contour areas provided by Polk County Land and Water Conservation Dept., 2010.

index for Bone Lake is 2.5, indicating that it is polymictic or mixes on numerous occasions during months when the lake is free of ice. This would allow released phosphorus from the sediment to reach the water column and be available for production of algae before fall mixing.

This analysis summarizes data collected to determine the in situ internal phosphorus load from anoxic sediments in Bone Lake. The focus is on the growing season due to reduced water clarity resulting from algae blooms in mid-late summer. It does not quantify the potential internal load during winter months. This analysis also utilizes past data regarding external load. This includes tributary monitoring in 2010 and land use that was completed in 2010 and 2012. The land use determination was completed in 2010 based on 2006 aerial photos. The land use analysis was conducted by and provided by the Polk County Land and Water Conservation Dept.

Methods

In situ determination of internal load for Bone Lake incorporated the collection of integrated phosphorus samples at ice out and then twice per month from May until September. Near bottom (~1 meter above sediment) hypolimnion total phosphorus samples were obtained at the approximate beginning of anoxia and near the end of anoxia to determine the net accumulation of phosphorus in the hypolimnion. Anoxia was defined as dissolved oxygen <1 mg/L. In cases where anoxia continued after collection, the concentrations were adjusted based upon the average release rate.

The following equation is used to quantify the phosphorus accumulation in the hypolimnion :

In-situ internal load (total) = $(TP_{t2})(V_{t2}) - (TP_{t1})(V_{t1})$ (Nurnberg, 2009)

This calculation was cross referenced with the internal load calculator-growing season mean method in the Wisconsin Lakes Modeling Suite (WILMS) (Panuska, 2003).

The phosphorus release was also calculated using volume weighted mean phosphorus concentration before whole lake mixing (early anoxia) and after whole mixing occurred. This value may account for phosphorus released during mixing if stratification is weak. This calculation was also cross referenced using the WILMS in situ method for determining internal loading (Panuska, 2003).

If mixing occurs during the summer, the internal load can be difficult to determine. To address this issue, the UW-Stout Limnological Research and Rehabilitation Center conducted a sediment phosphorus release rate from incubated sediment cores in June 2017. This release rate allows for the determination of internal phosphorus release potential, and the internal load is calculated using the release rate and the duration of anoxia.

Total sediment release = (release rate)(area of anoxia)(duration of anoxia)

The lake model BathTub was used to evaluate the calculated internal load with the potential external load and the seasonal phosphorus concentration. The model was calibrated using the inflow of water volume and phosphorus mass data as well as the outflow water volume and phosphorus mass data. Two perennial tributaries were evaluated in 2010 and 2012 for flow and nutrients, which allowed for calibration of the non-point load. The outflow provided a more precise calibration of the model than in years past when outflow was not measured. This allowed for hydrologic load calibration.

Dissolved oxygen/temperature profiles were collected in 24 locations ranging from 7 meters to 13 meters in depth to determine the duration and area of anoxic conditions as well as the degree of stratification. See figure 1 for these locations.

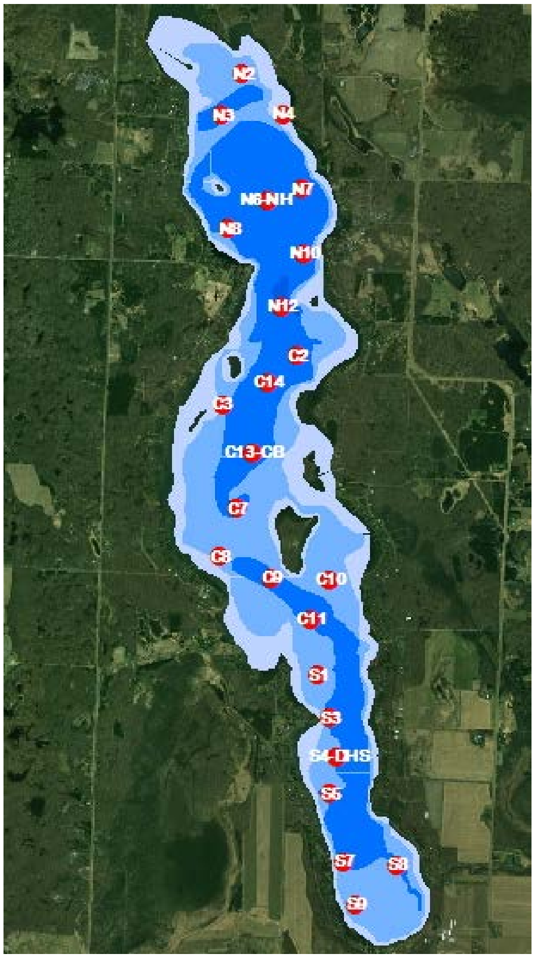


Figure 1: DO/Temperature profile sites. Profiles were conducted weekly from May until Sept.

The profiles were analyzed to determine duration and area of anoxia throughout the lake. This duration can be calculated using the following equation (AF is anoxic factor)(Nurnberg, 2004) :

$$AF(summer) = \frac{(t_1)(a_1)}{A_0} + \frac{(t_2)(a_2)}{A_0} + \frac{(t_3)(a_3)}{A_0}$$

AF is defined as the anoxic factor, which is an area weighted mean duration of anoxia in days, where t_n is the time that area is anoxic in days, a_n is the area of anoxia of t_n duration, and A_0 is the total area of anoxia in the lake during the entire anoxia duration.

A release rate was then determined using:

Release rate = Mean Total Internal load (kg) / Area (m^2)/# of anoxic days (AF) = mg/m^2/day

Results

The monitored integrated phosphorus samples show a continuous increase in total phosphorus from May until mid-July each year 2015-2017. This is followed by a more substantial increase from mid-July to early/mid-August. It appears Bone Lake begins to mix extensively by mid-August, which is represented by the large phosphorus spike from mid-August to late September. Figure 2 shows the mean total phosphorus each year (data from all three basins). Figure 3 is the average of all basins for all three years.

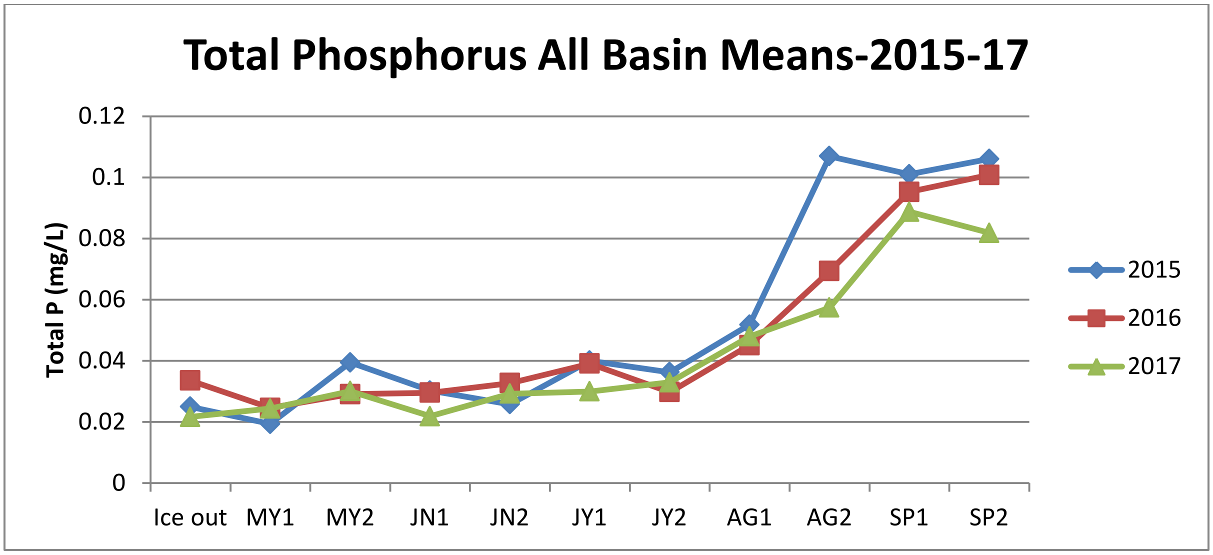


Figure 2: Total phosphorus concentration from integrated samples collected in 2015-2017.

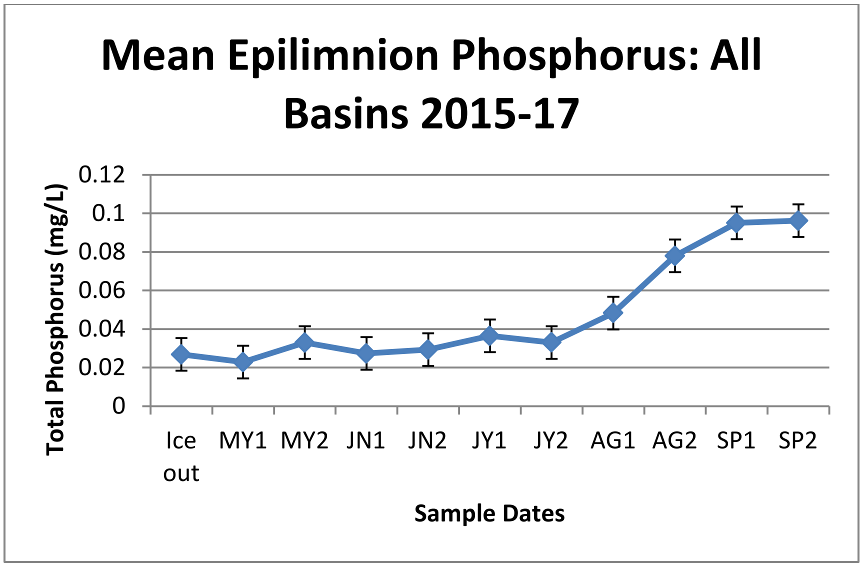


Figure 3: Mean total phosphorus in epilimnion all basins for years 2015 to 2017.

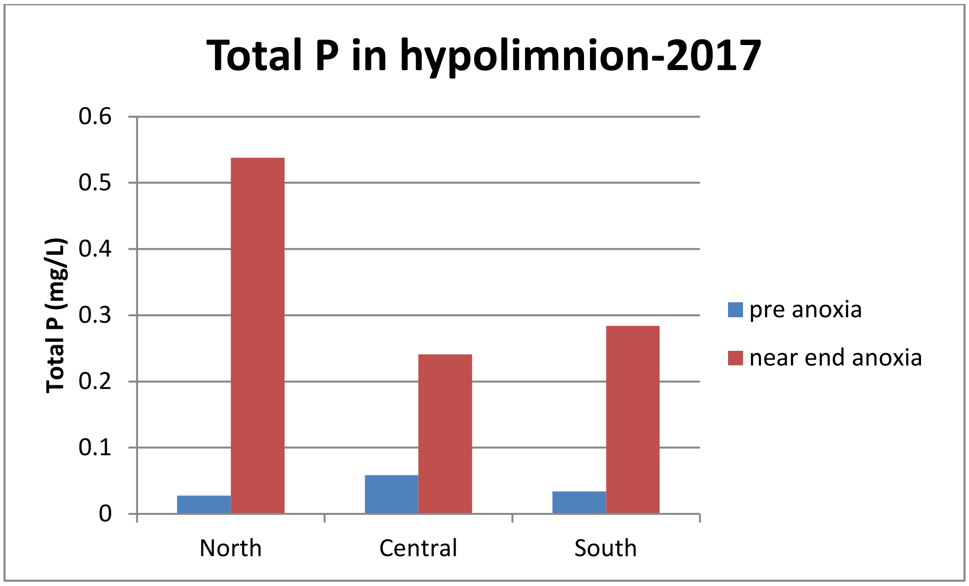


Figure 4: Hypolimnion phosphorus accumulation from sediments in 2017. The hypolimnion was most stable in 2017 so best reflects the potential accumulation in each basin.

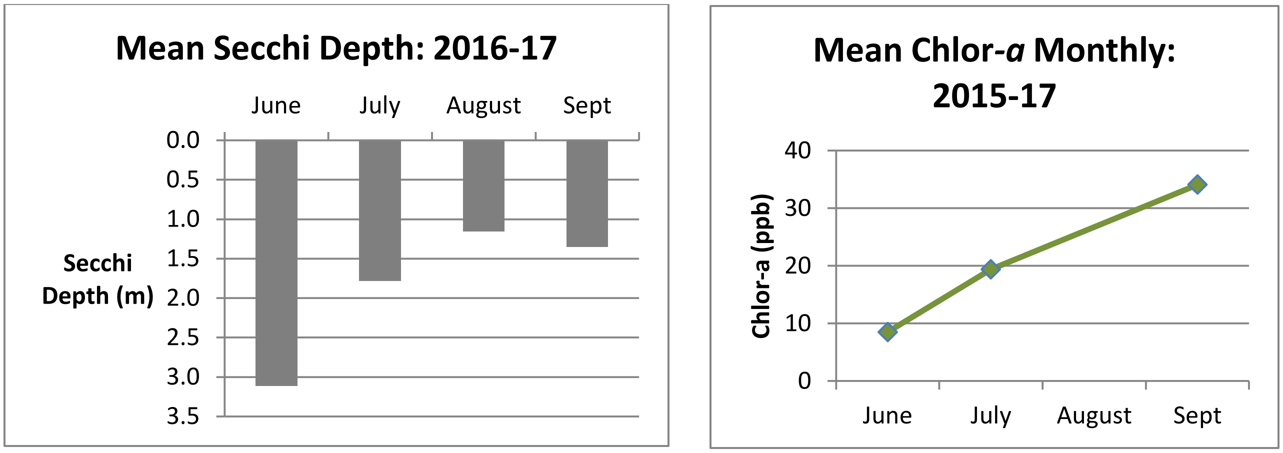
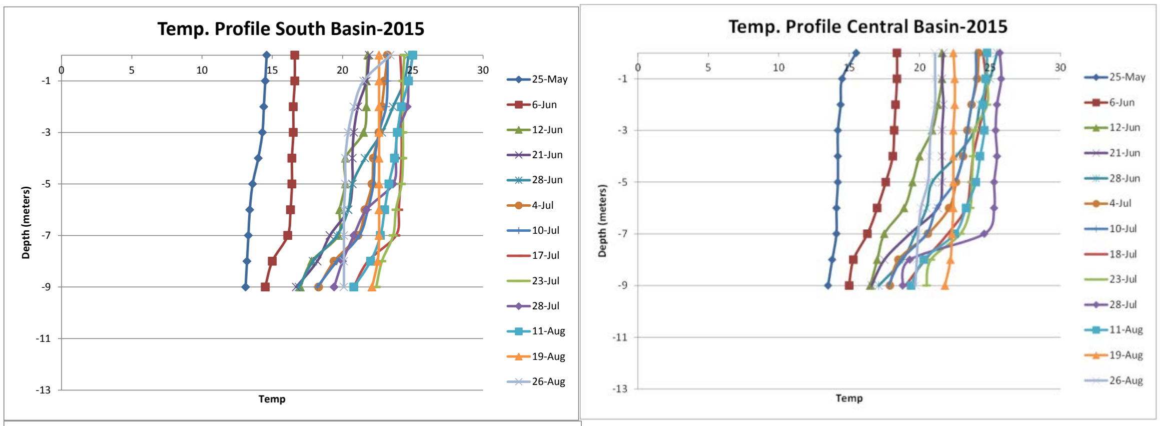


Figure 4: Observed mean secchi depth and chlorophyll-a data 2015-17.

Citizen monitoring collects consistent secchi depth readings and limited chlorophyll a measurements. Both of these data show significant changes in secchi depth and chlorophyll-a concentrations later in summer. The secchi depth decreases beginning in July and continues into August. The chlorophyll-a concentrations increased significantly later in summer, ending about 4 times higher in September. These data demonstrate the effect of internal load release later in the summer season (figure 4).



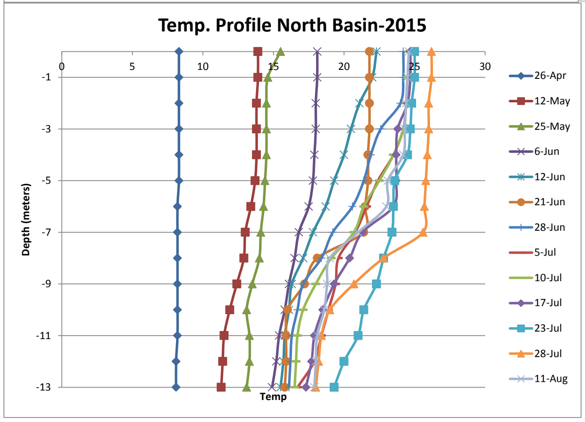
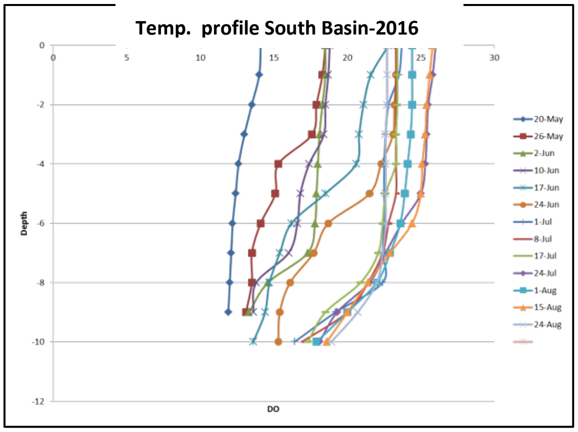
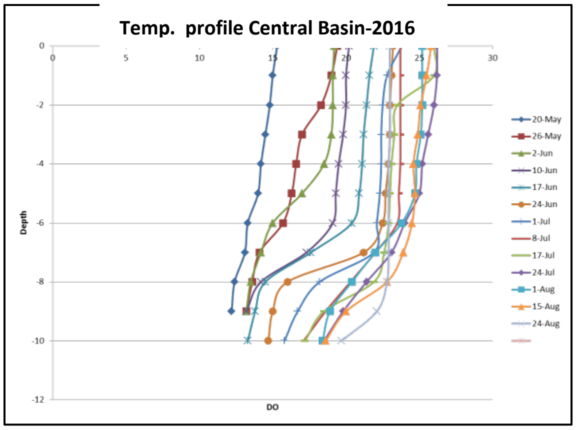


Figure 5: Temperature profile at representative basin sample location 2015.





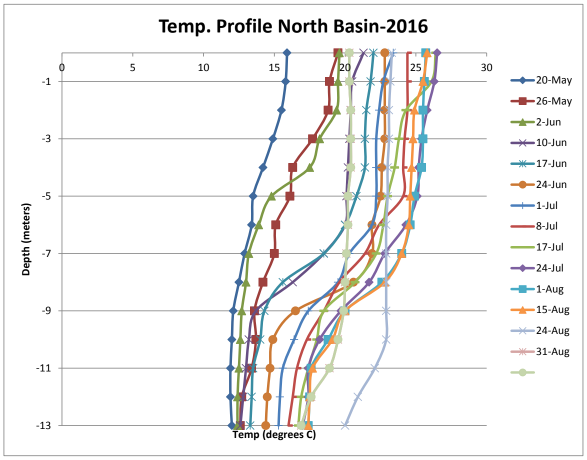
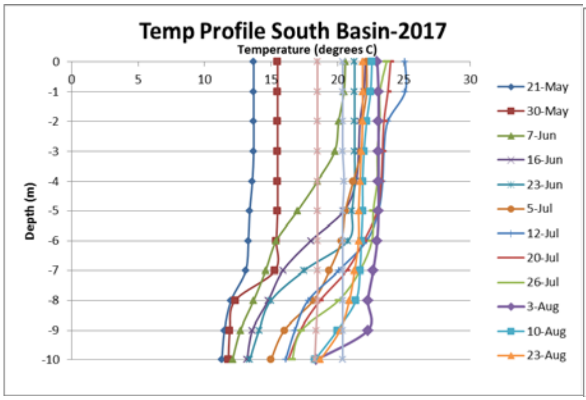
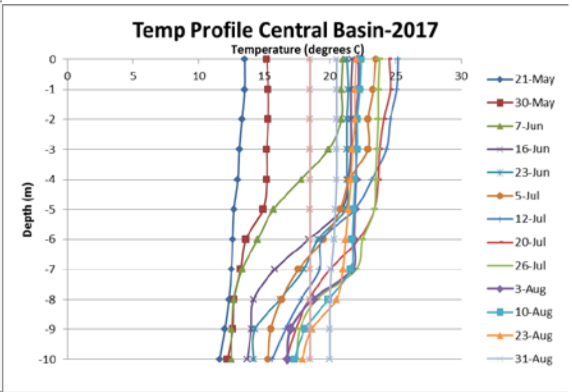


Figure 6: Temperature profile at representative basin sample location 2016.





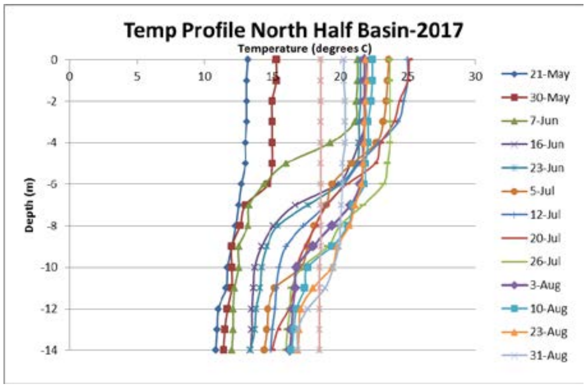


Figure 7: Temperature profile at representative basin sample location 2017.

Bone Lake varied from year to year in terms of anoxic conditions and stratification. 2015 showed weakest stratification in 2015, followed by 2016 and 2017 respectively. Table 1 shows the mean difference in temperature between the epilimnion and hyplimnion. In most sample locations the thermocline occurred 1-2 meters above the sediment surface.

The temperature profiles show that the stratification is not significant, with small temperature differences between the epilimnion and hypolimnion. The thermocline, when present, occurs in most all locations from 7-8 meters. The stratification was most stable in 2017 and between the basins the most stable in the north basin and the least stable in the south basin. Figures 5-7 show represented profiles from one location in each basin.

BASIN	Mean Depth sample point (m)	Epilimnion/ hypolimnion °difference 2015	Epilimnion/ hypolimnion °difference 2016	Epilimnion/ hypolimnion °difference 2017
North	9.6	3.4	4.2	5.7
Central	8.9	3.6	4.6	5.4
South	8.9	2.8	3.9	4.2
Mean	9.1	3.3	4.2	5.1

Table 1: Temperature difference from June to August in each basin for each year. This is to reflect the lack of stable stratification in Bone Lake.

The number of days of anoxia at ~1m above the sediment was the least in 2015, followed by 2016 then 2017 respectively. This lower anoxia at just above sediment along with weak stratification was supported by apparent phosphorus release into the epilimnion that was higher in 2015. In time periods that the water just above sediment surface was not anoxic, the water at the sediment level was anoxic, thus likely allowing phosphorus release during these time periods. Table 2 shows the mean duration of anoxia at various depths (measured ~1 meter above sediment level) at the sample locations. Figures 8-10 show the DO profile for each year at sample points of basins.

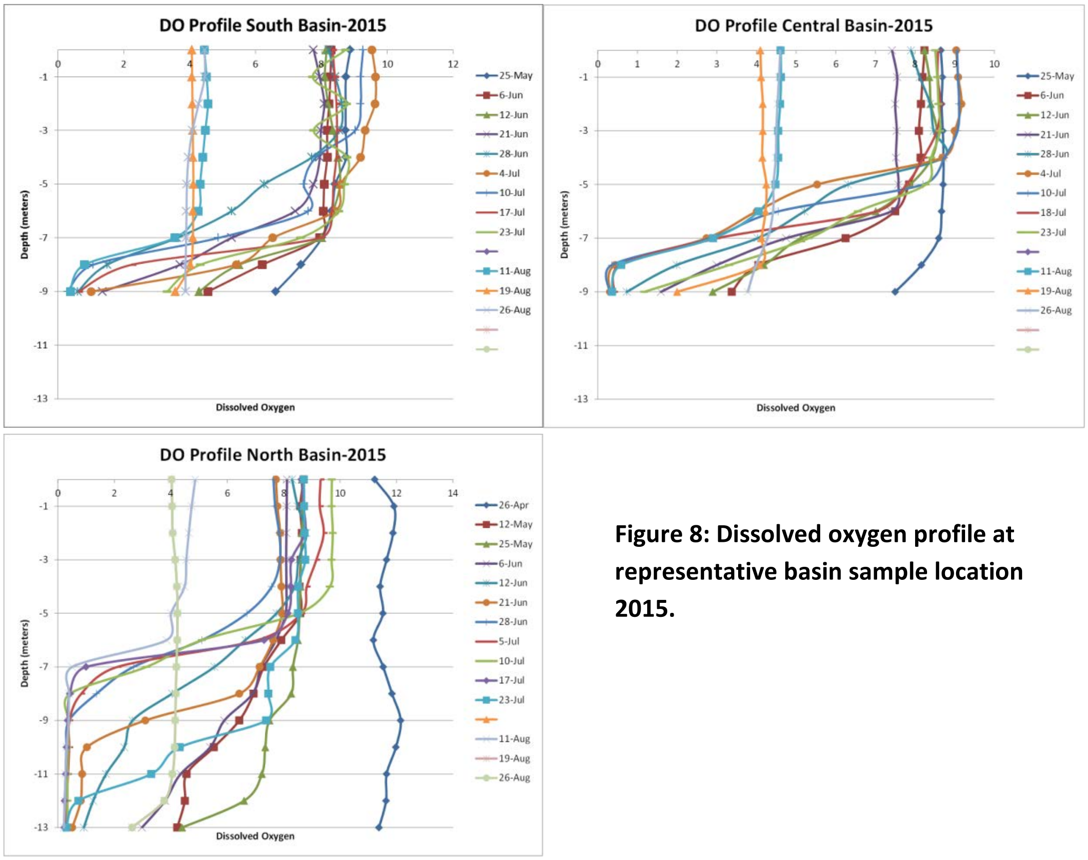


Figure 8: Dissolved oxygen profile at representative basin sample location 2015.

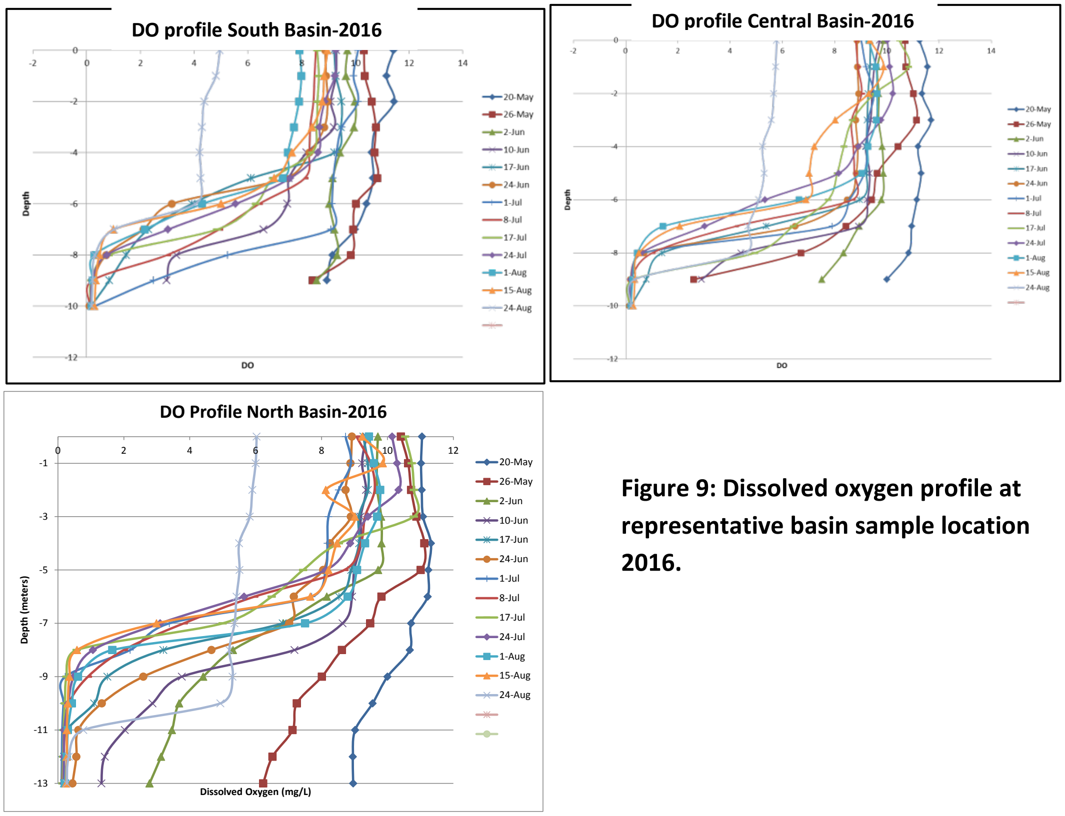


Figure 9: Dissolved oxygen profile at representative basin sample location 2016.

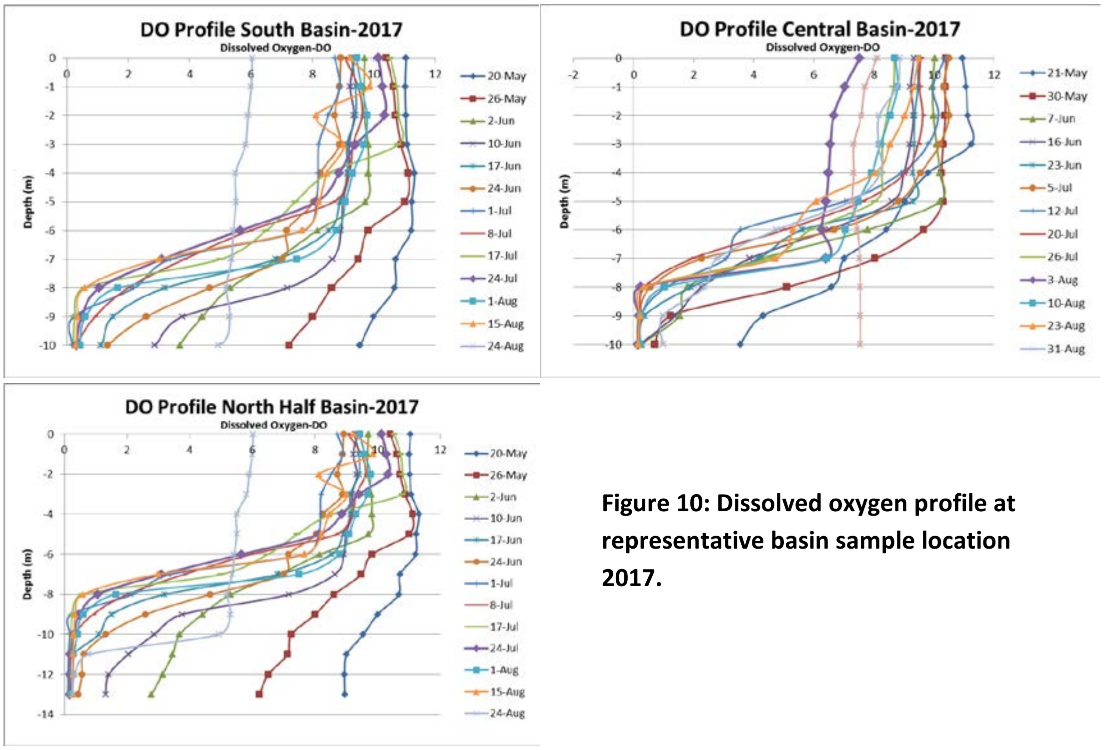


Figure 10: Dissolved oxygen profile at representative basin sample location 2017.

Depth of anoxia (just above sediment)	Mean Days 2015	Mean Days 2016	Mean Days 2017	Mean Days 2015-17
8m	51	62	59	57.3
9m	62	70	67	66
12m	64	83	100	82.3
Area weighted mean anoxia duration	60	70	71	67
AF (for entire lake area)	30	35	35	33.3

Table 2: Anoxic duration (in days) at each depth and the area weighted mean for anoxia in Bone Lake each year.

The data shows that anoxia duration was longer and at a more shallow depth in 2017 than in 2015 and 2016. The sediment was anoxic in most areas in 2015 and 2016 during times when the water ~1m above was not. This would allow for phosphorus release and increase internal loading. Anoxia (and stratification) was most pronounced each year in the deepest hole in the north basin. The south basin has the most sporadic anoxia, with some points showing alternating oxic and anoxic conditions from week to week.

Method	**2015 (kg)**	**2016 (kg)**	**2017 (kg)**	**Mean all years**	**Mean release (mg/m^2/d) for entire lake area**
Hypolimnion volume weighted accumulation	*Mixed prior to obtaining samples**	1570	1598	1584	6.75
Volume weighted before and after anoxia/mixing whole lake	1870	1668	1544	1694	7.22
Core sample release (based on AF for each year)	1328	1549	1549	1505	6.42(from core sample data 2017)
Mean sediment load all methods	1599	1596	1564	1594	6.8

*DO/Temperature profiles indicate weak stratification and likely mixing into epilimnion, reducing accumulation and no valid determination.

Table 3: Summary on internal load calculations for each year using both methods.

There was accumulation of phosphorus measured in 2016 and 2017. The hypolimnion mixed prior to collecting the second sample (end of anoxia) since in 2015 the timing for the full lake mix was unknown. The accumulation was smaller in 2016 than in 2017, but the profile and DO profile data suggests the thermocline was less developed, increasing the chance for mixing between layers.

Following mixing in mid-late August, the phosphorus spiked higher in 2015 and 2016, as compared to 2017, which had a longer anoxia time. All three years showed a large increase in phosphorus in the epilimnion in August (following full lake mix). Based on the profile data, the stratification was more substantial in 2017 reducing release of phosphorus into the water column until late in the growing season. External loading was higher in 2015 and 2016 with more precipitation occurring than in 2017. Some of the rain events were intense in 2015 (and somewhat in 2016). Some events occurred about the same time that the full lake mixing occurs in early August. A large rain event in late July could have contributed to the phosphorus spike in early August, but be attributed to internal loading rather than external.

Model Summary Year	**External (kg)** (runoff+ atmosphere+ septic)	**Internal (kg)** (sediment+ CLP)	**Predicted TP (µg/L)**	**Observed TP (µg/L) June-Sept**	**Predicted Chlor-*a* (µg/L)**	**Observed Chlor –*a* (µg/L)[#]**	**Predicted Secchi (m)**	**Observed Secchi (m)**
2015	1865	1770	60	62	23	21.5	1.8	2.0
2016	1523	1767	56	55	22	*33.4	1.8	1.75
2017	1068.2	1735	49	49	21	20	1.8	1.8
Modeling Mean 2015-17	**1451**	**1767**	**54**	**55**	**22**	**21.5**	**1.8**	**1.85**

*Only two samples taken, both in Sept. 2016 causing high value therefore taken out of mean.

[#]Very limited chlorophyll data so mean is July and Sept. for 2015 and 2017.

Table 4: Summary of external and internal loading as well as predicted and observed lake data.

Modeling the lake with Bathtub resulted in total loads higher in 2015, followed by 2016 then 2017 respectively. The predicted total phosphorus, chlorophyll and secchi depths indicate a good fit of the model using the internal and external loads listed. The water and phosphorus budget (inputs and output) were completely in balance.

***Mean Model Predictions with mitigation of phosphorus* (June-Sept)**	**Total Phosphorus (µg/L)**	**Chlorophyll-a (µg/L)**	**Secchi depth (meters)**
Mean 2015-17	54	22	1.8
No sediment release	34	12	2.6
No sediment or CLP release	31	10	2.7

Table 5: Model predictions for total phosphorus, chlorophyll-a, and secchi disk if no internal loading occurs.

Load Source	**Mean load 2015-2017**	**% of total load**
External sources (precip., septic, runoff)	1451	45.1%
Internal sources (sediment and CLP)	1767	54.9%

Table 6: Mean external and internal load amounts years 2015-2017 and percent of total load.

The lake model using external and internal phosphorus loads showed that over the three year average, the internal load made up 55.8% of the total phosphorus load (table 6). This percentage ranged in what appears to be due to precipitation differences. In 2015, the external loading accounted for 51% while internal accounted for 49% of the total load. However, in 2017 when there was less precipitation and less intense rain events occurred, the external load accounted for 38% of the total while the internal load was 62% of the total load.

In addition, Bone Lake was modeled eliminating all internal loading, leaving only external sources for the lake nutrient predictions (table 5). The model predicts better water quality with the elimination of the internal load. This allows for a general prediction of the effect of mitigation of the internal load.

Discussion

Conclusions from data

The in situ internal load data from 2015 to 2017 shows that the internal loading of phosphorus from sediments is a substantial portion of the total nutrient load. The three year average was 1594 kg, including the core sediment release values determined in 2017. This accounts for 50% of the mean total load during 2015-2017. The two methods differed in loading masses calculated, with the hypolimnion accumulation method showing a lower total amount. This could be due to partial mixing of the lake earlier than August allowing phosphorus to be released from the hypolimnion into the epilimnion. This would reduce the accumulation, but contribute to higher phosphorus concentration. Overall, it could also be due to a larger area of anoxia that occurred but was not reflected in the data.

The modeling of external loading in Bone Lake predicts a mean epilimnion phosphorus concentration of 34 μg/L. This is significantly lower than the observed epiliminion phosphorus, which can be accounted for when internal loading is included. The predicted results are close to the observed, thus reflecting a substantial internal load from anoxic sediments.

The data reveals that the lake is likely mixing to some degree during the summer. This mixing is likely different in various regions of lake. The profile data shows weaker stratification, especially in 2015. Furthermore, the south basin shows weaker stratification than the central and north basins on average. The difference in temperature between epiliminion and the hypolimnion is small in all basins, but smallest in the south followed by the central and north respectively. Water is more dense as it gets colder, with a maximum density at 4°C (~40°F). The colder the hypolimnion water and greater difference from the epilimnion temperature, the more stable the stratification. It appears that the most stable stratification occurred in 2017, which showed longer anoxia duration as well. 2015 was the least stable and still had a high internal load.

Anoxia duration will affect the release of phosphorus. In the 2015 and 2015, the duration of anoxia ~1 meter above the sediment level was shorter than in 2017. However, the internal loads appear as high or higher than in 2017. This may be due to more mixing during the summer due to less stable stratification. This would result in higher concentration of phosphorus in the epilimnion. It is possible that the sediment was anoxic and releasing phosphorus, but ~1 meter above it was not anoxic due to mixing. During long stable stratification periods, some phosphorus will likely settle back into the sediment. Regardless, each year shows a large release of phosphorus when the lake mixes in early to mid-August. Even though the hypolimnion seems to be less stable and the thermocline just above the sediment in any given year, there is a significant release of phosphorus when the lake mixes completely in August.

Although Bone Lake is considered polymictic, the degree of mixing seems to be variable and the late phosphorus load suggests the lake shows limited mixing before August. However, the stratification seems to degrade early, thus making the phosphorus available for algae growth during August when the epilmnion is still warm. The epilimnion phosphorus concentration does slowly increase from early to mid-summer, prior to a full mix in August. All of this increase cannot be accounted for by the external load, which is evidence the thermocline is unstable enough to allow phosphorus release from the hypolimnion. However, the marked increase in phosphorus concentration in the epilimnion in early to mid-August suggests that the most substantial mixing occurs later in the summer rather than throughout the summer. It is likely that the more subtle mixing in mid-summer contributes to decreased water clarity. By early August in each year, the phosphorus release was significant, followed by increases in chlorophyll concentration and degradation of water clarity.

The lake model estimating external load plus internal load resulted in a mass balance phosphorus concentration close to the actual phosphorus concentration measured in lake. The imprecision in modeling external load can be significant as the model is estimating loading based upon land use and how the land will affect the water and nutrient budget. This model included extensive flow and nutrient data of two perennial tributaries, thus eliminating the estimation from this land area. The land cover from these two tributaries was also used to calibrate the land use export coefficients. The model also used extensive outflow volume and nutrient data. This allowed for more precise calibration of the model. The internal load was determined using a large lake data set as well. Therefore, the predicted external load fit into the mass balance model. This load should be a good prediction for comparison to the internal load and the total load of phosphorus.

The variability in total loading seemed to be in response to precipitation differences between the years. In 2015, there was much more rainfall that also occurred during some intense rain events. In contrast, in 2017 there was much less precipitation and the external load appeared to be much less, therefore making up much less of the total load. In the final analysis, the internal load consistently led to a large increase in total phosphorus during mixing, while the lake responded with higher precipitation amounts with a higher total phosphorus load. Both sources are significant contributors in the total phosphorus load amounts.

Historically there does not appear to be a strong correlation between precipitation amounts and the total loading. If the total load is largely due to external loading from tributaries and land, then in high precipitation years, the total phosphorus would increase and the secchi should decrease. In low precipitation years, the total phosphorus would decrease and the secchi should increase. If the total load is largely due to the internal loading, then high precipitation years would have less effect on the total load, and could even increase the secchi by flushing the lake. The historical precipation amounts correlated with secchi does does not appear to show a strong trend (appendix figure 2). The variability could be due to intensity of rain events contributing to the total precipitation (fewer more intense storms vs more less intense storms) and/or anoxia duration and mixing of hypolimnion. This variability supports the phosphorus load data suggesting that the external and internal sources are both significant contributors.

The UW-Stout Limnological Center reported a sediment phosphorus release rate of 6.42 mg/m^2/day (James, 2018). Considering the area weighted mean for anoxia duration and the area is on anoxia, this rate would lead to a mean internal load of 1505.2 kg for the three years . This closely matches the calculated hypolimnion accumulation determined from in lake data. The fact that these loading values are consistent with one another suggests that the calculated internal load is valid.

Management implications

There is a substantial phosphorus release from anoxic sediments in Bone Lake. This sediment phosphorus release is higher than the external load. The availability of the phosphorus in the epilimnion does seem to vary as the summer progresses. With weak stratification, there is likely mixing into the epilimnion in mid-summer which can account for increased algae growth in July. The stratification although weak, does appear to be stable enough to accumulate phosphorus which leads to a substantial release of phosphorus in August, when the lake mixes. This mixing is early resulting in significant algae blooms during the month of August and into September.

Mitigation of internal loading should result in significant reduction in phosphorus concentrations in the epilimnion, which would result in reduced algae blooms and increased water clarity. Since the spring overturn phosphorus levels are substantially lower than in the fall, much of the retained phosphorus is undergoing sedimentation back into the bottom sediments. If the sediments do not release this phosphorus, it should reduce concentrations immensely.

If the internal loading is mitigated, is would likely need to be coupled with management practices to further reduce external loading. Paleolimnological data suggests that the seasonal nutrient levels in the lake have improved somewhat since the 1990's (Edlund and Williamson, 2017). However, if external loading of phosphorus is high enough to maintain eutrophic levels in the epilimnion, algae blooms could continue, albeit less severe. In addition, this external load could contribute to more accumulation of phosphorus in the lake sediments. During the study, Bone Lake did respond with much higher external phosphorus loading when there was more substantial precipitation and intense rain events (2015). This was coupled with evidence of more mixing which could be attributed to more storm events. A more in-depth analysis of the land use may be warranted to make phosphorus mitigation more of a success. There has been some analysis of sub-watersheds through culvert analysis, but more ground truth work could be done to eliminate internal drainage areas that don't drain directly into the lake. Land use could also be updated using lidar technology. This technology allows the mapping of flow into the lake based upon precise topography data.

There are other sources of phosphorus that have been evaluated in years past. In 2012, it was determined that approximately 187 kg of phosphorus could be released from the invasive species *Potamogeton crispus* while it decomposes in July and August. Since *Potamogeton crispus* (CLP) is being managed, this amount is estimated at 171 kg due to fewer acres of dense CLP now compared to 2012. This phosphorus would be part of the epilimnion concentrations, which may account for some higher internal load calculations compared to the hypolimnion accumulation. Septic systems could be an external load source. This amount has been evaluated, but this was through estimation of resident numbers and using WILMS to model. A septic load of 67 kg was used for this model. Again, this amount of loading is represented to some degree in the epilimnion sample's concentration. Reduction in septic loading would reduce external loading. Finally, in some cases groundwater can contribute phosphorus. Certain bedrock types can lead to high phosphorus concentration in ground water. No published groundwater data could be obtained for reference and was not considered in the model since the potential load is unknown. It was assumed that the net groundwater budget is zero, but may not be the case.

References

Edlund, M.B., and J. Williamson. 2017. A Paleolimnological Study of Bone Lake, Polk County, Wisconsin: Fossil Algal Pigments. Final Report to Bone Lake Management District. St. Croix Watershed Research Station, Science Museum of Minnesota, Marine on St. Croix, Minnesota. 7 pp.

Edlund, M.B., Ramstack Hobbs, J. and Williamson, J. 2015. A Paleolimnological Study of Bone Lake, Polk County, Wisconsin. Final Report to Bone Lake Management District. St. Croix Watershed Research Station,
Science Museum of Minnesota, Marine on St. Croix, Minnesota.

James, William. Examination of sediment phosphorus fluxes and aluminum sulfate dosage considerations for Bone Lake, Wisconsin. 2018. UW-Stout Limnological Research and Rehabilitation report.

Nurnberg, Gertrud K. Assessing internal phosphorus load-Problems to be solved. *Lake and Reservoir Management.* 2009. 25: 419-432.

Nurnberg, Gertrud K. Quantified Hypoxia and Anoxia in Lakes and Reservoirs. *The Scientific World Journal.* 2004. 42-54.

Nurnberg, Gertrud K. Prediction of annual and seasonal phosphorus concentrations in stratified and polymectic lakes. *Limnology and Oceanography.* 43(7). 1998. 1544-1552.

Nurenberg, Gertrud K. Quantifying anoxia in lakes. *Limnology and Oceanography.* 40(6). 1995. 1100-1111.

Nurnberg, Gertrud K. The Prediction of Internal Phosphorus Load in Lakes with Anoxic Hypolimnia. *Limnology and Oceanography.* 29(1). 1984. 111-124.

Osgood, Richard A. Lake mixing and internal phosphorus dynamics. *Arch. Hydrobiologia.* 113(4). 629-638.

Panuska, John C. and Jeff C. Kreider. Wisconsin Lakes Modeling Suite. *Wisconsin Department of Natural Resources.* October 2003.

Panuska, John C. and Richard A. Lillie. Phosphorus Loadings from Wisconsin Watersheds: Recommended Phosphorus Export Coefficients for Agriculture and Forested Watersheds. *Bureau of Research- Wisconsin Department of Natural Resources.* 1995.

Sondergaard, Martin. Jensen, Jens Peder. and Erik Jeppesen. Role of sediment and internal loading of phosphorus in shallow lakes. *Hydrobiologia*. 2003. 506-509: 135-145

Sondergaard, Martin. Jensen, Jens Peder. and Erik Jeppesen. Retention and Internal Loading of Phosphorus in Shallow, Eutrophic Lakes. 2001. *The Scientific World*. 1: 427-442.

Taube, Clarence M. Ch. 12: Three Methods for Computing the Volume of a Lake. *Manual of Fisheries Survey Methods II*. January 2000.

Van der Molen, Diedrik T. and Paul C. M. Boers. Influence of internal loading on phosphorus concentration in shallow lakes before and after reduction of the external loading. 1994. *Hydrobiologia*. 275/276: 379-389.

Walker, William W. Jr. PhD. BathTub (version 6.1): Simplified Techniques for Eutrophication Assessment and Prediction. *USAE Waterways Experiment Solutions*. April 2004.

Appendices

Appendix Table 1: Total phosphorus readings from integrated epilimnion samples (mg/L).

Total Phos. Epilimnion	Ice out	MY1	MY2	JN1	JN2	JY1	JY2	AG1	AG2	SP1	SP2
2015	0.025	0.019	0.039	0.030	0.026	0.040	0.036	0.052	0.107	0.101	0.106
2016	0.034	0.025	0.029	0.030	0.033	0.039	0.030	0.045	0.069	0.095	0.101
2017	0.022	0.024	0.030	0.022	0.029	0.030	0.033	0.048	0.057	0.089	0.082

Appendix Table 2: Total phosphorus readings from near bottom hypolimnion samples (mg/L).

Hypolimnion Total Phos.	**Start anoxia**	**End anoxia**	**Start anoxia**	**End anoxia**	**Start anoxia**	**End anoxia**
Basin	**2015**	**2015**	**2016**	**2016**	**2017**	**2017**
North Basin	0.0503	0.0814*	0.115	0.514	0.0275	0.538
Central Basin	0.0328	0.0885*	0.115	0.216	0.0584	0.241
South Basin	0.0377	0.0742*	0.115	0.0811*	0.0339	0.284
***mixed**						

Appendix Table 3: DO readings near bottom and number of days of anoxia.

			Days of anoxia		
Sample pt	Depth (ft)	Depth (m)	2015	2016	2017
N2	28	8.5	47	56	69
N3	25	7.6	7	0	43
N4	32	9.8	67	69	62
N6	32	9.8	60	69	62
N7	32	9.8	56	69	69
N8	31	9.4	63	55	69
N10	33	10.1	76	69	62
N12	43	13.1	76	83	100
North Mean		9.8	64	67	70
C2	32	9.8	67	60	76
C3	20	6.1	0	0	0
C7	30	9.1	52	69	69
C8	26	7.9	14	7	21
C9	34	10.4	60	76	76
C10	29	8.8	45	69	62
C11	32	9.8	60	76	76
C13	31	9.4	53	76	69
C14	34	10.4	67	76	86
Central Mean		9.1	58	72	73
S1	27	8.2	14	14	0
S3	33	10.1	67	73	69
S4	31	9.4	56	76	76
S5	31	9.4	60	76	78
S7	30	9.1	60	76	43
S8	31	9.4	60	76	76
S9	28	8.5	53	76	52
South Mean		9.2	59	76	66

Appendix Table 4: Precipitation amounts.[2]

Month	2015	2016	2017
April	1.58	4.71	2.95
May	4.29	1.91	4.91
June	3.69	3.93	4.8
July	8.51	5.49	3.25
August	6.66	5.17	4.29
Sept	4.89	3.98	1.09
Total (in)	29.62	25.19	21.29
Total (m)	0.752	0.640	0.541
3 yr Mean	0.644 (m)		

Appendix Table 5: Contour areas and volumes.

Contour	area (acres)	Depth range	Acre-feet
0+	1704	0-10.0	14888.5
10+	1341.6	10.0-20.0	12287.7
20+	1119.3	20.0-30.0	8255
30+	563.2	30.0-40.0	2120.7
40+	7.6	40.0-44.0	25.3
		Total	**37577.2**

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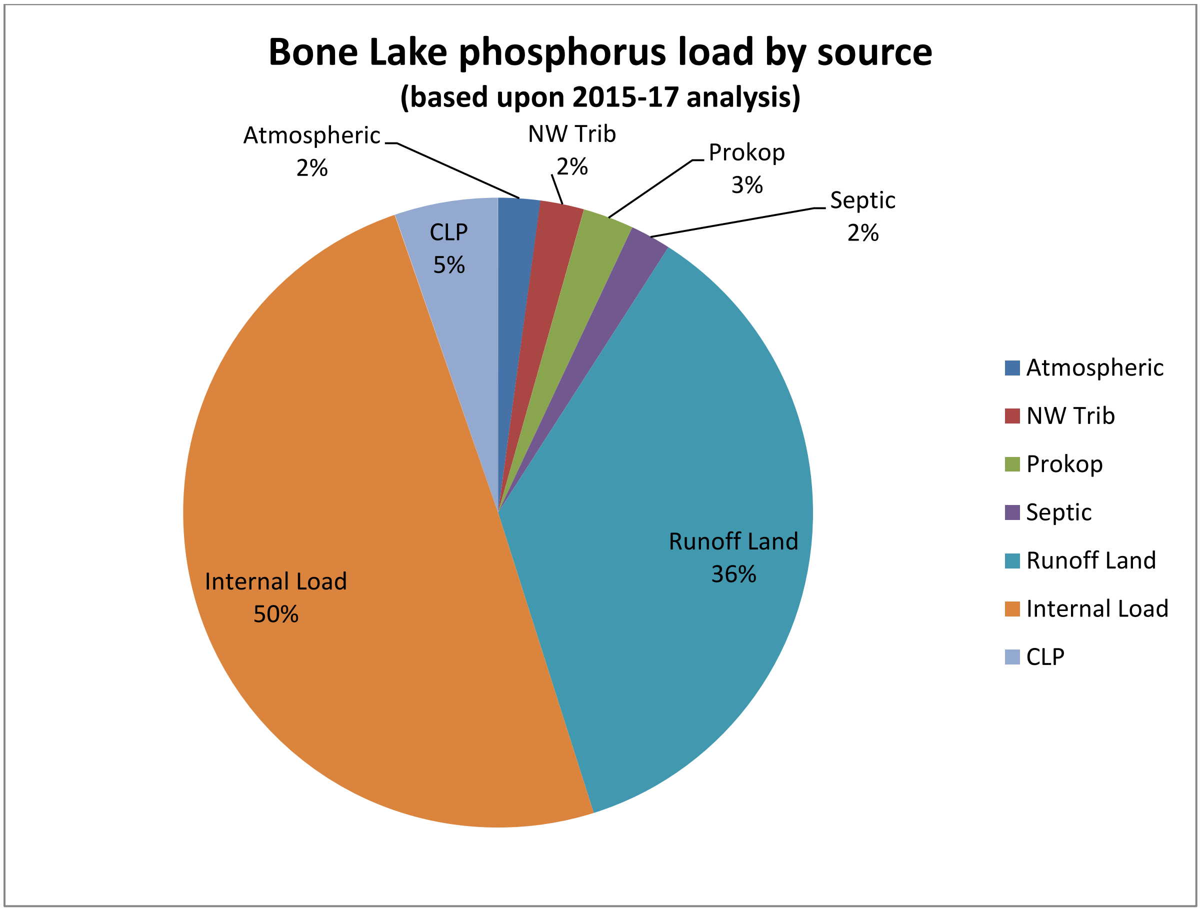
[2] From NNW Amery Data at https://www.cocorahs.org/WaterYearSummary/

Appendix Figure 1: Total Load by % based upon mean 2015-17 model amounts.



Appendix Table 6: Bathtub modeling mass balances.

Default Case											
Overall Water & Nutrient Balances											
Overall Water Balance						Averaging Period =	0.50	years			
				Area	Flow	Variance	CV	Runoff			
Trb	Type	Seg	Name	km^2	hm^3/yr	(hm3/yr)^2	-	m/yr			
1	1	1	NW Trib	2.5	0.6	3.60E-03	0.10	0.24			
2	1	1	Prokrop	5.7	1.1	1.21E-02	0.10	0.19			
3	2	1	Bone Lake Pt		1.1	0.00E+00	0.00				
4	2	1	East Inflow		0.9	0.00E+00	0.00				
5	2	1	Hunting Grounds		1.3	0.00E+00	0.00				
6	2	1	NE Inflow		1.2	0.00E+00	0.00				
7	2	1	Station 1 West		0.6	0.00E+00	0.00				
8	2	1	Station 1 NW		0.5	0.00E+00	0.00				
9	2	1	Station 2 Middle East		0.2	0.00E+00	0.00				
10	2	1	Station 2 Middle West		1.3	0.00E+00	0.00				
11	2	1	Station 2 SE		0.7	0.00E+00	0.00				
12	2	1	Station 2 SW		0.4	0.00E+00	0.00				
13	4	1	Fox outflow		9.2	0.00E+00	0.00				
14	1	1	Septic		0.0	0.00E+00	0.00				
PRECIPITATION				6.9	9.0	3.22E+00	0.20	1.30			
TRIBUTARY INFLOW				8.2	1.7	1.57E-02	0.07	0.21			
NONPOINT INFLOW					8.0	0.00E+00	0.00				
***TOTAL INFLOW				15.1	18.7	3.24E+00	0.10	1.24			
GAUGED OUTFLOW					9.2	0.00E+00	0.00				
ADVECTIVE OUTFLOW				15.1	0.0	1.14E+01	9.99				
***TOTAL OUTFLOW				15.1	9.2	1.14E+01	0.37	0.61			
***EVAPORATION					9.5	8.16E+00	0.30				
Overall Mass Balance Based Upon				Predicted		Outflow & Reservoir Concentrations					
Component:				TOTAL P							
				Load		Load Variance			Conc	Export	
Trb	Type	Seg	Name	kg/yr	%Total	(kg/yr)^2	%Total	CV	mg/m^3	kg/km^2/yr	
1	1	1	NW Trib	72.6	2.3%	2.64E+02	14.6%	0.22	121.0	29.5	
2	1	1	Prokrop	83.6	2.6%	3.49E+02	19.4%	0.22	76.0	14.6	
3	2	1	Bone Lake Pt	149.6	4.6%	0.00E+00		0.00	134.2		

4	2	1	East Inflow	41.1	1.3%	0.00E+00		0.00	48.3		
5	2	1	Hunting Grounds	101.5	3.2%	0.00E+00		0.00	77.2		
6	2	1	NE Inflow	211.6	6.6%	0.00E+00		0.00	183.2		
7	2	1	Station 1 West	107.8	3.3%	0.00E+00		0.00	184.2		
8	2	1	Station 1 NW	55.8	1.7%	0.00E+00		0.00	109.7		
9	2	1	Station 2 Middle East	21.7	0.7%	0.00E+00		0.00	133.6		
10	2	1	Station 2 Middle West	185.3	5.8%	0.00E+00		0.00	144.3		
11	2	1	Station 2 SE	181.4	5.6%	0.00E+00		0.00	264.3		
12	2	1	Station 2 SW	103.0	3.2%	0.00E+00		0.00	279.7		
13	4	1	Fox outflow	495.2		3.46E+04		0.38	53.8		
14	1	1	Septic	67.0	2.1%	0.00E+00		0.00	5000.0		
PRECIPITATION				69.0	2.1%	1.19E+03	66.0%	0.50	7.7	10.0	
INTERNAL LOAD			(includes CLP 171 kg)	1767.0	54.9%	0.00E+00		0.00			
TRIBUTARY INFLOW (includes septic 67 kg)				223.2	6.9%	6.13E+02	34.0%	0.11	130.3	27.3	
NONPOINT INFLOW				1158.8	36.0%	0.00E+00		0.00	144.3		
***TOTAL INFLOW				3218.0	100.0%	1.80E+03	100.0%	0.01	171.9	213.4	
GAUGED OUTFLOW				495.2	15.4%	3.46E+04		0.38	53.8		
ADVECTIVE OUTFLOW				-0.4		3.32E+04		10.00	53.8		
***TOTAL OUTFLOW				494.8	15.4%	5.75E+04		0.48	53.8	32.8	
***RETENTION				2723.3	84.6%	5.89E+04		0.09			
	Overflow Rate (m/yr)			1.3		Nutrient Resid. Time (yrs)			0.7526		
	Hydraulic Resid. Time (yrs)			4.8952		Turnover Ratio			0.7		
	Reservoir Conc (mg/m3)			54		Retention Coef.			0.846		

Bathtub inputs

Tributary Data											
					Dr Area	Flow (hm^3/yr)		Conserv.		Total P (ppb)	
Trib	Trib Name		Segment	Type	km^2	Mean	CV	Mean	CV	Mean	CV
1	NW Trib		1	1	2.458	0.6	0.1	0	0	121	0.2
2	Prokrop		1	1	5.719	1.1	0.1	0	0	76	0.2
3	Bone Lake Pt		1	2	0	0	0.1	0	0	0	0.2
4	East Inflow		1	2	0	0	0	0	0	0	0
5	Hunting Grounds		1	2	0	0	0	0	0	0	0
6	NE Inflow		1	2	0	0	0	0	0	0	0
7	Station 1 West		1	2	0	0	0	0	0	0	0
8	Station 1 NW		1	2	0	0	0	0	0	0	0
9	Station 2 Middle East		1	2	0	0	0	0	0	0	0
10	Station 2 Middle West		1	2	0	0	0	0	0	0	0
11	Station 2 SE		1	2	0	0	0	0	0	0	0
12	Station 2 SW		1	2	0	0	0	0	0	0	0

13	Fox outflow		1	4	0	9.2	0	0	0	54.8	0
14	Septic		1	1	0	0.0134	0	0	0	5000	0
Tributary Non-Point Source Drainage Areas (km^2)			Land Use Category--->								
Trib	Trib Name		1	2	3	4	5	6	7	8	
1	NW Trib		0	0.0486	1.604	0.06075	0.122	0	0.486	0.1378	
2	Prokrop		0.4941	0.154	3.0335	0.1296	0.3362	0.66	0.9113	0	
3	Bone Lake Pt		0.29	0.14	1.03	0.085	0.049	0.31	0.13	0.081	
4	East Inflow		0.036	0.032	1.82	0.032	0.093	0	0.016	0.004	
5	Hunting Grounds		0.016	0.146	2.236	0.028	0.219	0.073	0.223	0.085	
6	NE Inflow		0.0016	0.0891	1.324	0.0486	0.0891	0.547	0.117	0.0527	
7	Station 1 West		0	0.0121	0.6116	0.02	0.344	0.061	0.036	0	
8	Station 1 NW		0.17	0.0012	0.562	0.0162	0.1053	0.036	0.0769	0.0284	
9	Station 2 Middle East		0	0	0.247	0	0.0822	0	0	0	
10	Station 2 Middle West		0	0.0122	1.81	0.02	0.518	0.1418	0.138	0.0122	
11	Station 2 SE		0.1296	0.0203	0.122	0	0.4739	0.174	0.0243	0	
12	Station 2 SW		0	0	0.122	0	0.328	0.0729	0	0	
13	Fox outflow		0	0	0	0	0	0	0	0	
14	Septic		0	0	0	0	0	0	0	0	
Non-Point Source Export Coefficients											
			Runoff (m/yr)		Conserv. Subs.		Total P (ppb)				
Categ	Land Use Name		Mean	CV	Mean	CV	Mean	CV			
1	Barren		0.8	0	0	0	100	0			
2	Forage		0.6	0	0	0	50	0			
3	Forest		0.39	0	0	0	20	0			
4	Grassland		0.4	0	0	0	50	0			
5	Residential		0.8	0	0	0	300	0			
6	Row Crop		0.8	0	0	0	400	0			
7	Wetland		0.2	0	0	0	20	0			
8	Open Water		0.62	0	0	0	20	0			

Appendix Figure 2: Precipitation and mean secchi comparison graph.