2019 Addendum to:

Lac Courte Oreilles, Sawyer County Phosphorus Site-Specific Criteria Analysis

WDNR Technical Support Document (2018)

12-19-2019

Wisconsin Department of Natural Resources

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Executive Summary

This 2019 Addendum supplements the Department's 2018 Technical Support Document titled "*Lac Courte Oreilles, Sawyer County: Phosphorus Site-Specific Criteria Analysis, WDNR Technical Support Document*". Based on the additional analyses described in this Addendum, WDNR has revised its previous 2018 recommendations and now proposes setting a site-specific total phosphorus (TP) criterion for Lac Courte Oreilles (LCO) at 10 ug/L. The additional analyses described in this Addendum were conducted by WDNR to address comments received from the public and from the United States Environmental Protection Agency (EPA) during the rulemaking process. The recommendation to establish a criterion of 10 ug/L TP is based on the following:

1. The current TP criterion of 15 µg/L is not protective for whitefish in the East Basin[1]. The additional analysis focused on the East Basin only, as it has the longest data record and is the deepest, most suitable part of the lake for whitefish. The Department did not reexamine oxythermal habitat for the West and Central Basins because the relationship between phosphorus and oxygen was inconclusive at those sites.
2. The additional analyses showed that a TP criterion in the range of 5 – 12 ug/L could improve oxythermal habitat for whitefish during critical warmer months, enabling survival during more years. Because the lowest mean annual TP concentration observed in the record was 6.3 µg/L, a target lower than this number is likely unrealistic for Lac Courte Oreilles. The recommended criterion of 10 µg/L TP is within the range of values recommended by our analysis.
3. Hypolimnetic temperature (temperatures in the cold, bottom layer of the lake) affects which TP concentrations would be protective for whitefish. In warmer years, which frequently occur, TP must be lower than 15 µg/L to provide any suitable oxythermal habitat for whitefish. However, even lower phosphorus concentrations will not assure that oxythermal habitat will always be available.

A TP criterion of 10 µg/L will not create fully suitable habitat for whitefish in all years. Temperature is a strong limiting factor and lower TP can only increase oxygen so much. Although lowering TP will not result in fully supporting suitable habitat for whitefish, it will improve whitefish resilience in the East Basin during stressful, warm years. Here, fully supporting suitable habitat means oxythermal habitat that provides for optimal growth, consumption, metabolism, and activity levels (at DO 6 mg/L or higher). The partial support that a lower TP would achieve could prevent mortality most years, but will still result in sublethal effects (at DO 3 mg/L, Hrycik et al. 2016). Thus, additional management actions beyond TP reduction alone would be necessary to fully support whitefish.

In the Department's 2018 Technical Support Document, the Department had determined that based on analyses available up to that point, there was insufficient evidence to conclude that reducing phosphorus concentrations would result in enough improvement of oxythermal habitat to fully support whitefish. Although this finding is still accurate, additional analysis in response to public comments indicates that phosphorus reductions could increase the oxythermal habitat enough to improve survival

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[1] This analysis found that Lac Courte Oreilles currently attains the oxythermal habitat requirements for cisco, the other coldwater fish species in Lac Courte Oreilles. Cisco can tolerate warmer temperatures than whitefish can, and a TP criterion lower than 15 ug/L is not necessary for cisco. Still, a lower TP concentration should provide improved oxythermal habitat for cisco also.

during more years. The analyses conducted in the original 2018 TSD are still valid and contribute to our broad understanding of Lac Courte Oreilles and the processes contributing to insufficient oxythermal habitat for whitefish. However, applying additional statistical approaches resulted in more nuanced findings. The key findings that led to a change in position are:

1. The 2018 TSD found a significant, positive relationship between TP and hypolimnetic oxygen demand using a thermocline depth of 10 meters (HOD_{10}) in the East Basin, but not in the other basins and not using a different metric of HOD. The lack of a relationship in other basins and the high degree of variability in the relationship made it difficult to derive a new criterion that was demonstrably different than the original criterion of 15 µg/L. One comment pointed out that there was not as much data available for the Center and West Basins, and therefore, WDNR may not have had the statistical power to detect a trend that might be present. This was a valid observation and WDNR proceeded by using a statistical technique that pooled data from all 3 stations together, thereby increasing power. WDNR then focused on the relationship between TP and HOD_{10} in the East Basin only in the next phase of analysis.
2. WDNR's original critique of Limnotech's approach to deriving a TP SSC was that they borrowed the coefficient describing the relationship between TP and HOD from a multi-lake study that included lakes with very high TP concentrations. This relationship may not hold within Lac Courte Oreilles, particularly because Lac Courte Oreilles' highest TP concentration is on the low end of the range of TP concentrations of the multi-lake study. WDNR's new analysis adopted Limnotech's approach, but applied the Lac Courte Oreilles-specific coefficient derived from analyzing LCO's data as described above. This approach allowed WDNR to quantify how lower TP would affect oxythermal habitat in the East Basin.
3. In the new analyses, WDNR also evaluated the effects of temperature and oxygen on oxythermal habitat in tandem. This allowed WDNR to account for temperature and better understand the variability in the relationship between TP and available oxygen.
4. These new analytical approaches allowed WDNR to better pinpoint the effect of TP on oxythermal habitat. The analyses showed that the current TP criterion is not protective of whitefish and that a lower TP criterion would provide more oxythermal habitat for whitefish in the East Basin. It allowed better understanding of the degree of oxythermal habitat that would be provided for whitefish given different levels of phosphorus in the East Basin. While phosphorus reduction alone will not result in oxythermal habitat that fully supports whitefish (eliminating sublethal and lethal effects), reduced phosphorus levels can increase the likelihood of survival over periods of stress during some warm years.

In the Department's 2018 TSD, there was too much variability in the results to show that a lower phosphorus concentration would result in improvements to oxygen levels. The above refinements to the Department's analyses improve upon its earlier work by making better use of lake-specific data to estimate the phosphorus-oxygen relationship in LCO, and by accounting for temperature in order to isolate the effect of phosphorus and quantify improvements to oxygen levels. These showed that there is a phosphorus-oxygen correlation in the East Basin, and that reducing phosphorus concentrations to a range of 6-12 ug/L could improve whitefish survival during some warm years.

This additional work provides site-specific, scientific documentation that a criterion of 10 ug/L is within a reasonable range to improve whitefish survival within the East Basin of the lake. However, given the other factors influencing the lake, fish kills are still likely to occur in some years with more severe weather conditions. Given that whitefish migrate into the lake from connected lakes that have more suitable whitefish habitat, the whitefish population may be maintained over time in Lac Courte Oreilles despite periodic fish kills.

Background

In 2018, WDNR undertook an analysis to assess whether a site-specific phosphorus criterion (TP_{SSC}) is appropriate for Lac Courte Oreilles, and if so, at what value it should be set. WDNR documented the findings of this analysis in a Technical Support Document (TSD) dated Feb. 23, 2018. That analysis found that there was insufficient evidence to support the conclusion that a lower phosphorus concentration would result in full support of oxythermal habitat for whitefish. In response to a subsequent court ruling WDNR proposed two options for rulemaking: a value of 10 µg/L for TP_{SSC} (as originally proposed by the Petitioners in the case) or no change in the existing statewide criterion of 15 µg/L.

Following the public hearing, WDNR received feedback that prompted a re-analysis of the potential link between phosphorus and coldwater fish kills. The original TSD (WDNR, 2018) showed that there was not enough evidence to conclude that decreased total phosphorus would result in a lower rate of hypolimnetic oxygen demand (HOD) and subsequent improvement of oxythermal habitat. It also showed that increased temperature was likely a stronger factor than oxygen demand in reducing oxythermal habitat. And third, it showed that there was not a significant reduction in oxythermal habitat during the same span of time when increased phosphorus concentrations were observed. These three lines of evidence indirectly suggested that lowering the phosphorus concentrations would not result in achieving suitable oxythermal habitat. However, WDNR did not establish a direct link between phosphorus and oxythermal habitat, primarily due to the complex interactions between nutrients, algae growth, and temperature.

In this re-analysis, WDNR attempted to re-examine whether there was a link between phosphorus and oxythermal habitat while simultaneously accounting for thermal effects. WDNR conducted the following analyses:

- Following comments on WDNR's 2018 TSD from LimnoTech (preparer for COLA, 2016), WDNR revisited the relationship between TP and HOD, while making better use of the available data. Using this new approach, the available LCO data showed a significant trend between TP and HOD, from which a coefficient could be extracted to adjust historical DO profiles based on various TP scenarios. This method was adapted from the LCO SSC report (COLA, 2016), except rather than using a coefficient that describes the relationship between TP and HOD across a wide range of lakes (Chapra and Canale, 1991), this re-analysis used a site-specific coefficient based on LCO data. Using this site-specific coefficient to adjust DO profile curves, WDNR estimated the ability to protect oxythermal habitat by reducing TP. Because oxythermal habitat is strongly influenced by temperature, in this case most strongly with respect to hypolimnetic mean temperature, WDNR estimated what concentration of TP is required to protect oxythermal habitat under different thermal conditions.
- A separate analysis was done to better evaluate the connection between the oxythermal layer thickness (OLT) and phosphorus directly, this re-analysis includes a set of models that detrend temperature from OLT to isolate the effect of phosphorus (including all stations simultaneously to make the best use of the available data). This analysis did not provide additional support for a lower criterion but is included for completeness.

These steps and their results are detailed in the next sections of this document.

Attainment of Water Quality Criteria in Main Basins

Lac Courte Oreilles is attaining applicable water quality criteria for TP and thresholds for chlorophyll *a* and aquatic macrophytes (WDNR, 2018, Sections 5.1, 5.2, and 5.3, respectively), but does not meet DNR's proposed water quality criteria for oxythermal habitat in two-story fishery lakes (Section 5.4, WDNR, 2018). The proposed water quality criterion for oxythermal habitat is based on the vertical thickness of a layer of the water column where both temperature (species-specific) and dissolved oxygen (DO, 6 mg/L) are simultaneously suitable (Figure 1). Lac Courte Oreilles contains both cisco and whitefish, and because whitefish are the more sensitive species, the OLT target that applies to LCO uses a maximum temperature of 18.9°C. The proposed rule states that the minimum annual observed OLT must be greater than 1 meter; if the minimum annual observed OLT is less than 1 meter for 2 or more of the past five years[2], the lake would be considered impaired for oxythermal habitat. While LCO achieves suitable OLT for cisco, it does not currently have suitable OLT for whitefish at any of the three deep-hole monitoring stations.

Assessing whole lake vs separating Musky Bay

The department's standard protocol for phosphorus assessments on lakes is to assess the lake's phosphorus criterion only at the deep point(s) of the lake. However, in 2012 COLA requested that the department do a separate phosphorus assessment within Musky Bay. The department agreed to that request but specified that it could not apply the two-story fishery TP criterion to the bay, since the bay is not two-story fishery habitat and has designated uses (aquatic life and recreation) more akin to a shallow drainage lake. Therefore, DNR applied the shallow drainage lake criterion of 40 ug/L TP. In the department's 2018 TSD DNR conducted analysis of Musky Bay to assess its phosphorus levels and its response indicators: chlorophyll *a* concentrations and its aquatic plant community. However, whereas in 2012 the bay had exceeded TP of 40 ug/L and was listed as impaired, by 2018 the bay had lower TP concentrations attaining its criterion, and also attained chlorophyll *a* and plant community thresholds. In the 2018 TSD DNR recommended that Musky Bay be delisted as impaired for phosphorus in the 2020 assessment. After the 2018 TSD was completed, because of these findings DNR and the Petitioners in the case agreed to discontinue assessing the bay separately and return to treating the lake the same as other lakes in the state, where a single lake criterion is assessed at the deep points of the lake (in this case, East, Central, and West Basins). A lake's criterion is not assessed within the bays, because bays naturally have different characteristics and more variable conditions based on wind direction, etc. If the lake's phosphorus criterion is not attained at any one or more of the three deep points, then the lake as a whole would be listed as impaired.

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[2] The department's proposed assessment protocols for the proposed OLT criterion have been revised since the draft version that was available when the 2018 TSD was written. The 2018 TSD stated "The proposed OLT assessment deems a two-story fishery lake to be impaired if, within the last 10 years, more than one out of three years has a minimum OLT of less than 1 meter", and its Table 8 showed attainment status for each basin based on that previously proposed assessment protocol. The revised proposal adopted by the Natural Resources Board in October, 2019 (but not yet promulgated) reads: "If any 2 or more years within the most recent 5-year period are exceedance years, the lake is not attaining the water quality criterion and shall be listed on the section 303 (d) list. If insufficient data are available from the most recent 5-year period, data from up to 10 years may be used if representative of current conditions." However, this does not change the results shown in Table 8 of the original TSD.

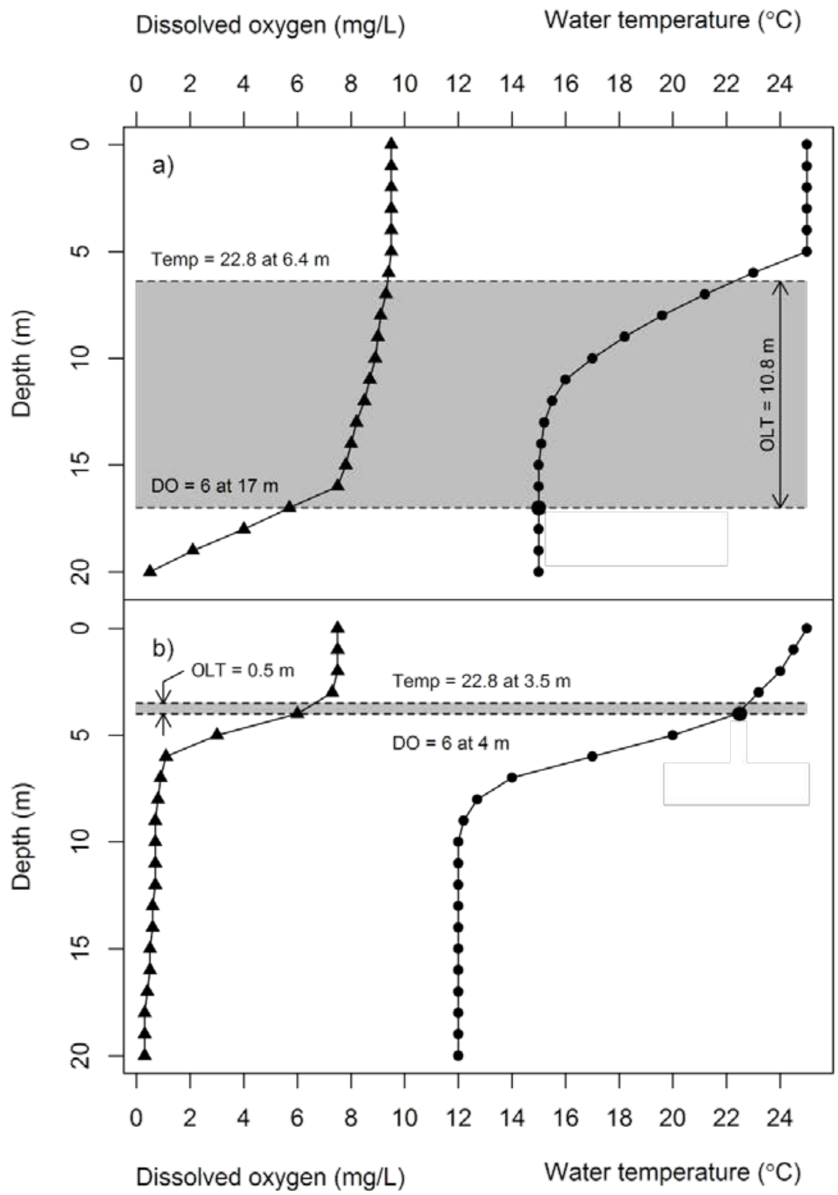

Figure 1. Dissolved oxygen (triangles) and temperature (circles) profiles, and the calculation of oxythermal layer thickness (OLT, shaded) from these profiles (adapted from Lyons et al, 2018). This example shows OLT for cisco, using a maximum temperature of 22.8°C (for whitefish the maximum temperature is 18.9°C) and a DO of 6 mg/L. The top boundary of the oxythermal layer is at the depth with the maximum temperature for the target fish species. The lower boundary of the oxythermal layer is at the depth where DO is 6 mg/L.

Site-Specific Phosphorus Criterion Based on the Relationships between Total Phosphorus, Temperature, and Hypolimnetic Oxygen Demand

WDNR reevaluated the relationship between TP and HOD recognizing that temperature also influences respiration rates and could describe some of the variation in the response of HOD to TP. WDNR found that hypolimnetic temperature influences the TP concentration that would improve oxythermal habitat for whitefish. Thus, temperature should also be considered in the final choice of the appropriate TP criterion. Although phosphorus concentrations less than the current criterion of 15 ug/L would improve oxythermal habitat in years when the hypolimnion is warmer, even the most extreme reductions in phosphorus will not result in an oxythermal layer thickness that would meet the criterion of 1 m water thickness at 18.9°C and 6 mg/L DO. Phosphorus concentrations ranging from 6 – 12 ug/L TP would provide better oxythermal habitat when hypolimnetic temperatures are warm (>11°C).

TP and HOD relationship specific to Lac Courte Oreilles

In 2016, LimnoTech prepared a report (COLA, 2016) describing a proposed TP_{SSC} based on the assumption that HOD would respond to lowered in-lake TP concentrations using a relationship between TP and HOD derived from a study across lakes of widely varying trophic state (Chapra and Canale, 1991). Although this assumption corresponds with limnological theory, WDNR rejected the proposal because the relationship that was used to describe the interaction between TP and HOD was not site-specific and may not hold at the low range of phosphorus concentrations observed in Lac Courte Oreilles. In the 2018 TSD, WDNR found a compelling relationship between TP and HOD, but the confidence intervals around the model fit were too wide to determine how the lake would respond to lowering in-lake TP concentrations. WDNR has revisited this relationship here.

In addition to the issue of the relationship between TP and HOD, the issue of how to relate that interaction to oxythermal habitat remains to be solved. LimnoTech provided a solution that predicts change in HOD given changes in in-lake TP concentrations (COLA, 2016), then adjusts the DO profile curve given the proportional change in HOD. To calculate HOD based on a TP_{SSC} they used the following formula derived from Chapra and Canale (1991):

Equation 1

$$HOD_{future} = HOD_{present} * (TP_{future}/TP_{present})^{0.478}$$

In the above formula, the coefficient value of 0.478 was derived from multiple lakes, but for this new assessment WDNR instead derived a site-specific coefficient to replace the multi-lake coefficient in Equation 1. WDNR also uses this new coefficient to estimate the effect of TP on OLT using LimnoTech's method for adjusting DO profile curves.

The 2018 TSD (WDNR, 2018) explored this relationship at all three deep-hole monitoring stations, East (deepest, official assessment location), Central, and West. There was a correlation between TP and HOD at the main deep-hole station (East), but not the other two stations. Originally, this correlation was derived independently for each station. In this re-analysis, WDNR pooled all data together within a mixed effects model that utilized the lme4 library of the R Statistical Programming language (Bates, 2014; R Core Team, 2019). The model took the form of the following formula, using R lme4 notation (Bates, 2014) where S is the monitoring station random effect:

Equation 2

$$\ln(AHOD_{10}) \sim \ln(TP) + (1 \mid S)$$

The above model relates the natural log of the areal HOD (g m^{-2} d^{-1}) below 10 meters of depth, to the natural log of annual average growing-season median surface TP, for each site-year combination, while varying the intercept for each station S. The resulting coefficient of the TP term corresponds to the exponent used in Equation 1, and the most likely coefficients for the east, central, and west basin are 0.41, 0.26, and 0.21 respectively. The following analyses focus on the East Basin and use 0.41 as the coefficient in Equation 1. The East Basin has the most data and is most likely to provide suitable oxythermal habitat. The Department did not reexamine oxythermal habitat for the West and Central Basins because the relationship between phosphorus and oxygen was inconclusive at those sites.

Deriving a TP criterion to provide sufficient oxythermal habitat

To assess the effect of a change in the TP concentration, we tested for changes in OLT that resulted in a change from the current standard of 15 µg/L (which functionally corresponds well to the observed ceiling because the maximum observed annual growing season mean was 14.7 in 1997) to concentrations between 1 and 20 µg/L, presuming that a new concentration will result in all years having concentrations lower than that value (i.e., always achieving suitable habitat). We tested for this effect using DO thresholds of 6 and 3 mg/L, and temperature thresholds of 18.9 and 22.8°C (lake whitefish and cisco thermal limits, respectively) to define OLT. All the above scenarios were tested in the east deep-hole station, and the results were tested for OLT > 1 m, OLT between 0 and 1, and OLT < 0 (Figure 2).

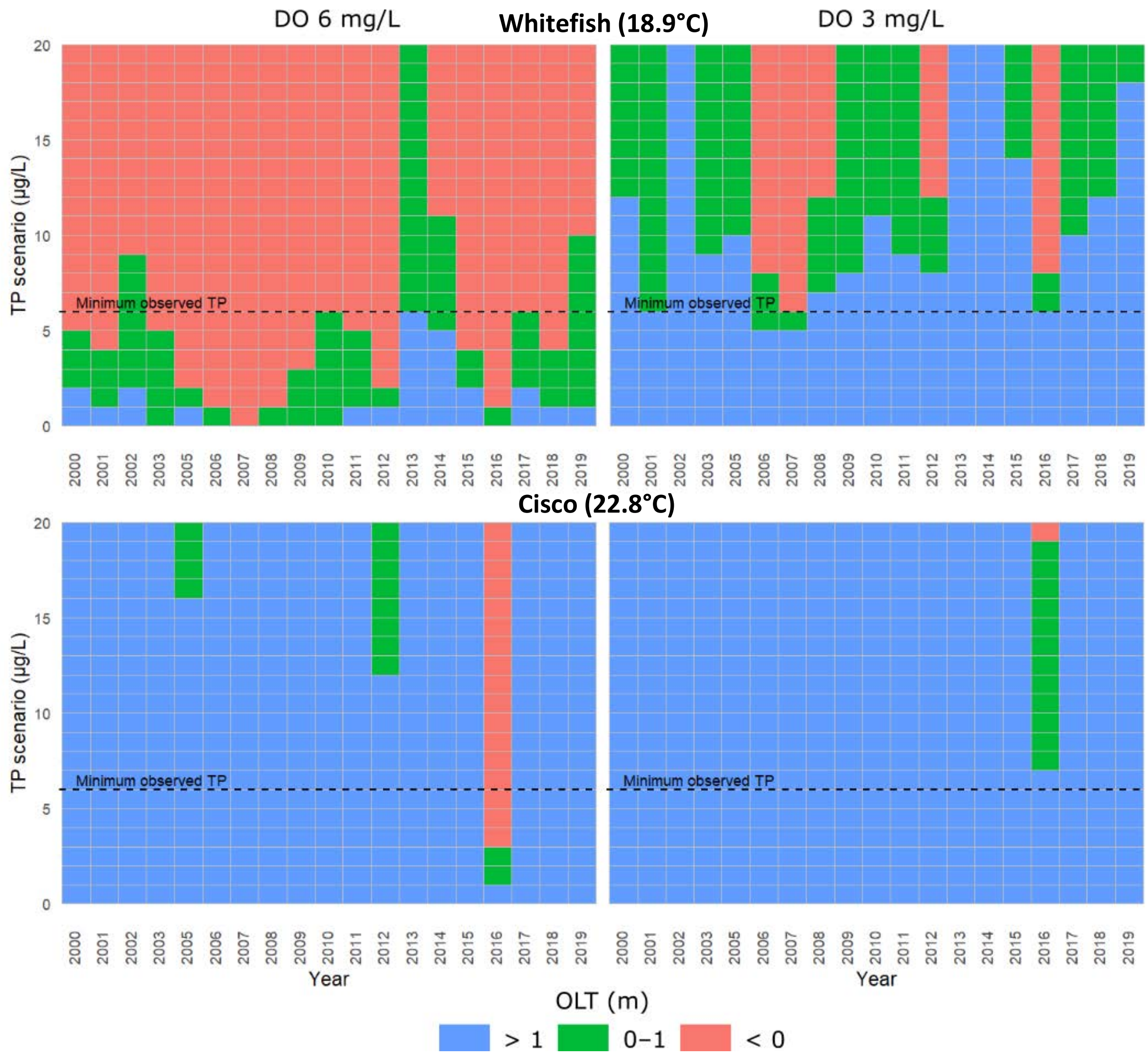

Figure 2. Oxythermal layer thickness (OLT) for a gradient of total phosphorus (TP) concentrations using thermal thresholds for both whitefish (top graphs) and cisco (bottom graphs) at two different thresholds of dissolved oxygen (DO), 6 and 3 mg/L. The x-axis is every year (except 2004), where each year represents the estimated OLT on the day when OLT was at its minimum. The "no-change" (i.e., existing conditions) scenario is when TP equals 15 µg/L. Pink grid cells indicate no habitat (0 meters), green cells indicated a "sliver" of habitat between 0 and 1 meters, and blue indicates greater than 1 meter of habitat. The black dashed line is the minimum observed mean annual TP concentration of 6 ug/L (rounded to the nearest integer) which was recorded in 1990 and 1996.

The proposed OLT criterion states that no more than 1 out of 5 years can have less than one meter of minimum annual OLT and defines OLT using a DO concentration of 6 mg/L. In all but one year, phosphorus would have to be lower than the minimum TP ever observed in the lake (6 ug/L rounded to the nearest integer) to fully support OLT for lake whitefish if we use a DO threshold of 6 mg/L. At a TP of 6 ug/L, the whitefish OLT would only be achieved in 2013 (Figure 2). However, if the DO threshold is lowered to 3 mg/L (closer to acutely toxic concentrations), depending on the choice of TP_{SSC} and which 5-year block is used for the assessment, LCO could potentially increase whitefish survival with improved oxythermal habitat at TP_{SSC} values of 6 – 10 ug/L. For cisco, the TP scenarios result in achievement of the proposed OLT criterion for any combination of TP_{SSC}, 5-year assessment block, and DO threshold. Therefore, no change in TP_{SSC} is necessary to protect cisco oxythermal habitat.

Even though phosphorus cannot be reduced to a low enough concentration to result in fully supporting whitefish as defined by the proposed OLT rule package, reduced phosphorus can result in improved oxythermal habitat for whitefish. For example, the DO threshold used to define OLT for whitefish in this lake can be reduced to a lower minimum concentration of 3 mg/L. Minnesota Department of Natural Resources uses the temperature at which DO is 3 mg/L for assessment. While whitefish are likely to be more stressed under a DO of 3 mg/L, they could potentially survive at those levels during stressful periods in the hottest part of the year. Or, the OLT depth threshold could be set at less than 1 meter. Adjusting each of these parameters shows that TP_{SSC} is highly sensitive to how the OLT criterion is expressed. Figure 3 shows multiple different ways of expressing OLT, and how TP_{SSC} could be set to meet OLT for each of those expressions.

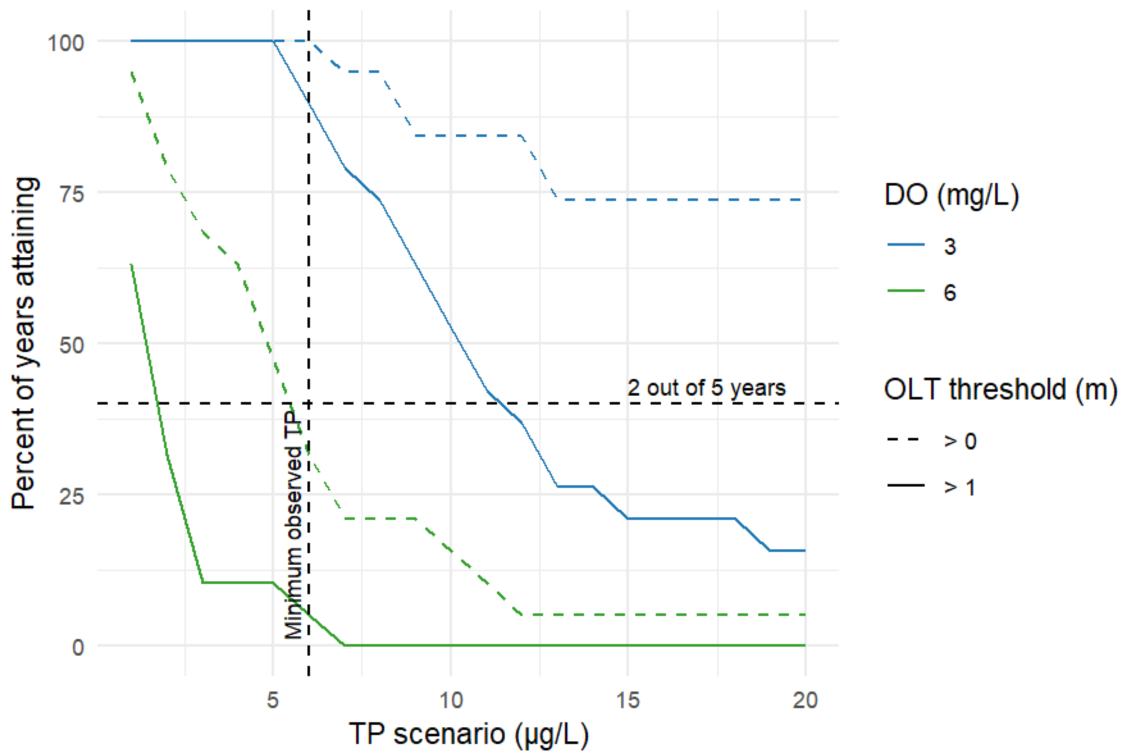

Figure 3. Percent of years when oxythermal layer thickness (OLT) would attain the proposed OLT criteria for a gradient of total phosphorus concentrations between 1 and 20 µg/L. The decision for what TP_{SSC} to use is highly sensitive to how the OLT criterion is expressed. For different thresholds of dissolved oxygen (DO) or minimum OLT, the TP_{SSC} could be very different. The vertical black dashed line is the minimum observed mean annual TP concentration in the East Basin, and can therefore be considered the lower end of potential phosphorus criteria. The horizontal black dashed line corresponds to the proposed OLT criterion, stating that if 2 or more out of 5 years have minimum OLT less than 1 meter, it is considered an impairment.

The band of OLT is often narrow during the critical summer period, and highly sensitive to changes in DO or water temperature. It is possible to estimate how reductions in TP could potentially improve OLT, but these estimates must be approached with caution because of uncertainty in the input models that predict OLT response and because these estimates presume a certain climate condition.

Effects of temperature and phosphorus on hypolimnetic oxygen demand

We explored the role of temperature in explaining the variation observed between years in the TP concentrations necessary to obtain OLT (Figure 2, Figure 3). We hypothesized that warm years would require an even lower phosphorus concentration to provide oxythermal habitat for whitefish. We further hypothesized that years when the TP concentration could be 15-20 µg/L were cold years.

We compiled a dataset to explore the combined effects of temperature and phosphorus on HOD, expecting that temperature is partially responsible for the variable TP concentrations necessary to provide oxythermal habitat between years (Figure 2). This analysis was limited to data from the East Basin deep-hole site, which has the most available data. We used the annual HOD estimates assuming a thermocline depth of 10 meters (HOD10) that were calculated in the 2018 TSD (WDNR, 2018). We used slightly different annual averages of TP than in the 2018 TSD, recognizing that there were data gaps some years because of a lack of TP data early in the summer. We instead calculated mean TP over two time periods: July 8 to August 11 and August 12 to September 15. We then averaged the two time periods to derive the annual mean TP concentration. There had to be at least one observation within each time period to obtain an annual average.

Next, we gathered temperature metrics from hindcast water temperature profiles derived from the General Lakes Model (Winslow et al. 2017, Table 1). These models simulate daily temperature profiles. The advantage of this (as compared to observed data from Lac Courte Oreilles) is that temperature metrics integrated over a longer time frame can be developed. This also eliminates the effect of sample design and frequency on calculated temperature metrics. Although the models predict surface water temperatures with high accuracy, there is more uncertainty in model predictions of deeper water temperatures. This should be kept in mind when interpreting the results.

Table 1. Annual temperature metrics from Winslow et al. 2017 used in the analysis to understand the drivers of Hypolimnetic Oxygen Demand (HOD) in Lac Courte Oreilles.

Temperature Metric	**Description**
Peak temperature (°C)	Maximum summer surface temperature observed each year
Stratification duration	Longest number of days that the lake is stratified (≥ 1°C difference across the profile)
Stratification onset day	First day (day of year, DOY) that the lake is stratified of the longest stratification period
Bottom temperature at stratification (°C)	Water temperature at 0.1 meters from the lake bottom on the stratification onset day
Growing Degree Days (T_{base} = 0°C)	Cumulative sum of daily surface temperatures (0 meters deep) that exceeded 0°C over the entire year
Mean surface temperature July Aug Sept (°C)	Mean temperature at 0 meters deep from July 1 to September 30
Max surface temperature July Aug Sept (°C)	Maximum temperature at 0 meters deep from July 1 to September 30

We then ran a random forest model including all the above variables and mean TP to predict HOD10. The random forest model does not assume an underlying data distribution and cannot be overfit, so it serves as a useful data exploration tool. The random forest model found that total phosphorus was the most important variable for predicting HOD10 followed by 3 temperature metrics: stratification duration, stratification onset day, and bottom temperature at stratification.

We then ran a linear regression model using total phosphorus and the bottom temperature at stratification to predict HOD10 and further explore these relationships. We natural log transformed HOD10 to meet the assumption of a normal distribution in a linear regression model. Both variables were significant predictors at $p<0.05$, and together they described 43% of the variation in HOD10 (Table 2). We focused on the bottom temperature at stratification to avoid overfitting, but the other temperature metrics could be used in the linear regression instead.

Table 2. Linear regression model on natural log transformed annual hypolimnetic oxygen demand.

Factor	Estimate	Standard Error	T value	p-value
Intercept	0.017556	0.026350	0.666	0.5161
TP	0.003750	0.001741	2.154	0.0492
Bottom temperature at stratification	0.005972	0.002607	2.280	0.0388

There was a positive relationship between TP and HOD and between bottom temperature at stratification and HOD (Figure 4). The observed HOD10 versus predicted HOD10 from this linear regression model (Figure 5) show that the predictions explain a relatively small fraction of the variability in HOD10 ($r^2 = 0.43$).

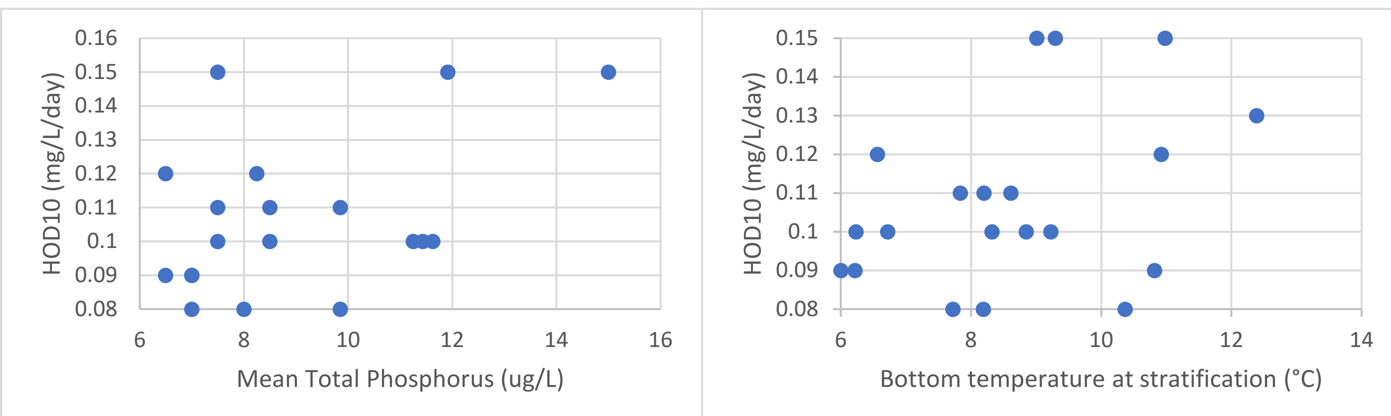

Figure 4. Scatterplots showing mean total phosphorus and HOD10 and bottom temperature at stratification and HOD10 in the East Basin.

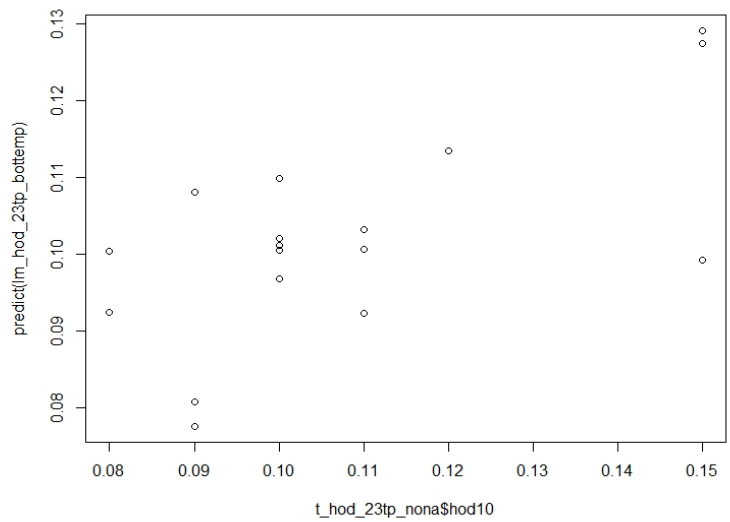

Figure 5. Observed HOD10 in the East Basin versus predicted HOD10 using the linear regression model summarized in Table 2.

The modeled temperature metrics show that the earlier in the spring that the lake stratifies, the colder the bottom temperature at stratification (Figure 6). The entire like has not had as much time to warm up, so the resulting bottom temperature is colder. Similarly, the earlier the onset day of stratification, the longer the total duration of stratification for the season. Finally, these two relationships mean bottom temperatures at stratification are colder in years with a longer stratification period.

All three temperature metrics were important for predicting HOD10. Respiration rates are faster at warmer temperatures. Thus, the stratification onset day is important for determining the hypolimnetic temperature and ultimately, the hypolimnetic oxygen demand. In warm springs when the lake thaws and stratifies early, the bottom temperature will be cooler and result in lower HOD for the year overall.

We reviewed epilimnetic temperatures in Lac Courte Oreilles during the period of each summer when OLT has been observed to be < 1 m thick (July 13 to September 14) to determine whether whitefish could survive in the epilimnion. The year 1977 was the only year when observed surface temperatures were less than 18.9° C (Figure 7). Furthermore, the maximum surface temperature during this period has significantly increased from 1975 to 2019 ($F= 12.45698$, $p= 0.0012$, Figure 7). Thus, whitefish habitat will have to be in the metalimnion and/or hypolimnion during this critical period in late summer. This means that sufficient oxygen must remain in these lower layers of water to support whitefish. Our analysis from here on focuses on hypolimnetic temperature and its effect on respiration rates rather than the direct effect of temperature on suitability for whitefish themselves.

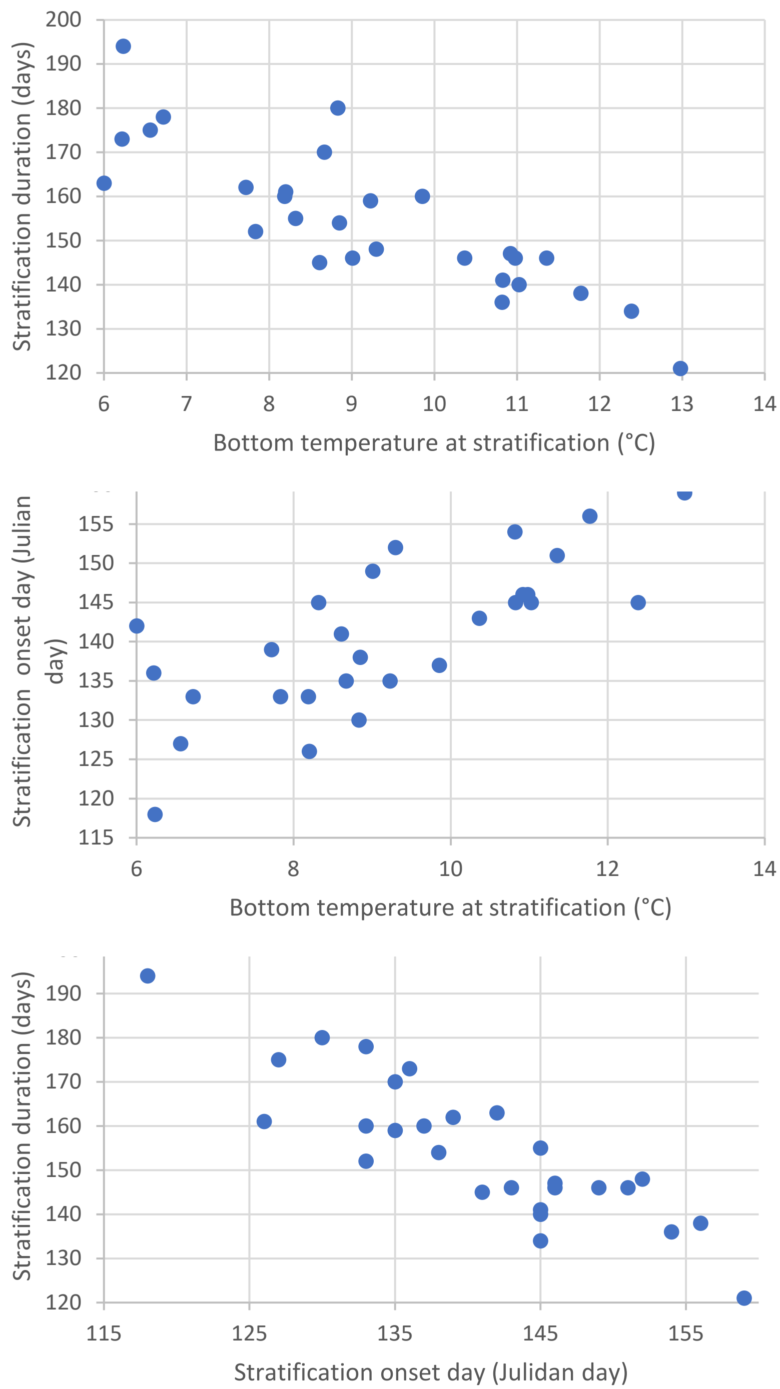

Figure 6. Correlations between thermal metrics related to stratification and hypolimnetic temperature in Lac Courte Oreilles (modeled results from Winslow et al. 2017).

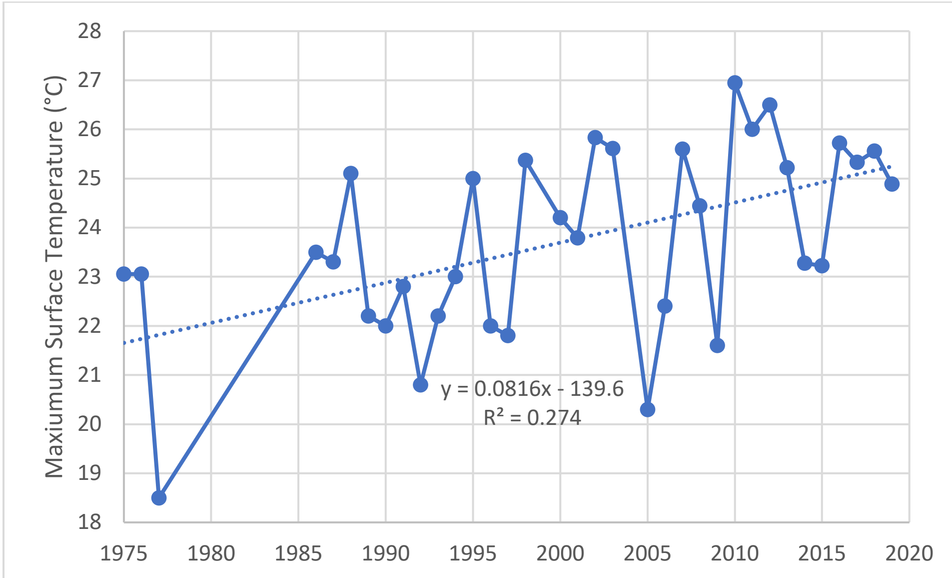

Figure 7. Maximum observed surface temperature between July 31 and September 10 each year in the East Basin

Protective total phosphorus concentrations given observed hypolimnetic temperatures in the East Basin

Whether the OLT is protective is less reliant upon the TP concentration than on the temperature. It can be useful to explore how TP impacts OLT by adjusting DO profiles based on changes in HOD, like the TP scenarios that are shown in Figure 2. However, in Figure 2, it becomes clear that each year is very different, not because of variation in TP, but because the weather was different in each year. Therefore, in order to better understand how reducing TP concentrations will result in improvements in oxythermal habitat, we investigated how achievement of the OLT based on a new TP concentration depends on annual differences in temperature. To assess this dependency, we extracted the estimated TP concentration that would result in achieving an OLT of > 1 meter, using a DO threshold of 3 mg/L, and whitefish thermal limit of 18.9°C. In other words, in the top-right panel in Figure 2, we identified the maximum value of TP for each year where the color of the grid cell is blue (indicating > 1 meter OLT). We then compared these TP values to metrics of temperature in the water column.

We found a significant negative relationship between the TP threshold required to obtain an OLT of 1 meter (at 18.9°C and 3 mg/L DO) and the mean hypolimnetic temperature on the same date ($F=12.087$, $p=0.0029$, Figure 8). As we hypothesized, a lower TP concentration is required when the hypolimnetic temperature is warmer to maintain some oxythermal habitat for whitefish. The current TP criterion for Lac Courte Oreilles of 15 ug/L would only be protective when the hypolimnetic mean temperature is 10.16°C or less. At mean hypolimnetic temperatures greater than 11°C, a lower TP concentration has the potential to protect whitefish habitat. Of the annual observations from the date with minimum OLT in the East Basin, the TP concentrations that would be protective range from 5 – 12 ug/L with a mean of 8 ug/L. The lowest mean TP concentration (from July 8 – September 15 each year) observed at the East Basin was 6.5 ug/L in 1990 and 1996. Mean TP summer concentrations have never been recorded as low as 5 ug/L.

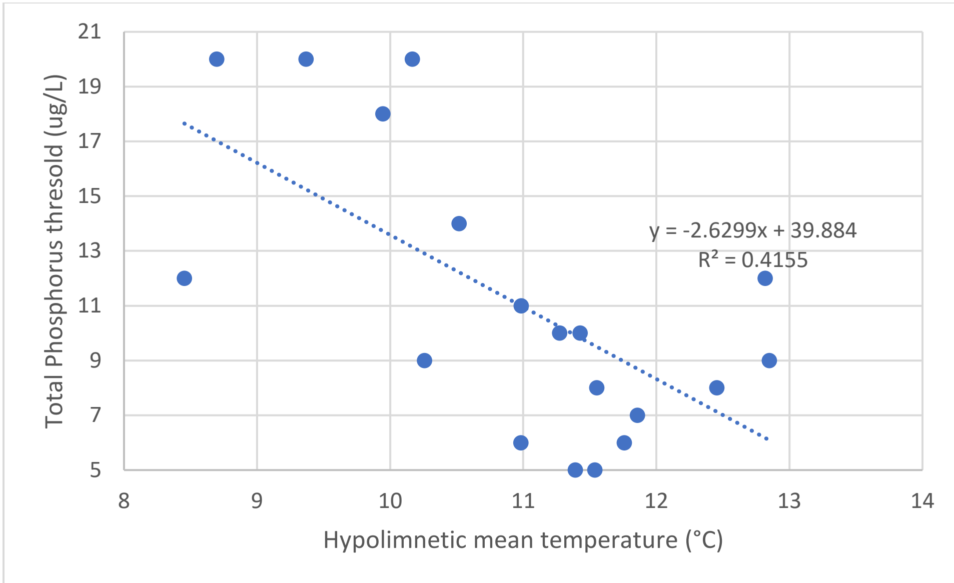

Figure 8. Total phosphorus threshold required to maintain an OLT of 1 m (18.9°C and 3 mg/L DO) in relation to the mean hypolimnetic temperature on the same date.

Because the phosphorus concentration that would provide oxythermal habitat depends on hypolimnetic temperature, it is important to understand how often various hypolimnetic temperatures occur. We compiled the mean hypolimnetic temperature from the East Basin deep hole site between July 13 and September 14 across all years. Daily data would be necessary to be certain about the distribution of hypolimnetic temperatures in Lac Courte Oreilles. Despite incomplete temperature records, we were still able to review the distribution of mean hypolimnetic temperatures on 126 dates from 1975 to 2019 (Figure 9). Over the years, the mean hypolimnetic temperatures on individual dates ranged from 7.5 to 16.3°C with a median of 10.6°C. The most frequently observed mean hypolimnetic temperatures were 11-12°C. Sixty-three percent of dates have a mean hypolimnetic temperature greater than 11°C. Because temperatures greater than 11°C are common, a phosphorus concentration lower than 15 ug/L would improve oxythermal habitat on most dates.

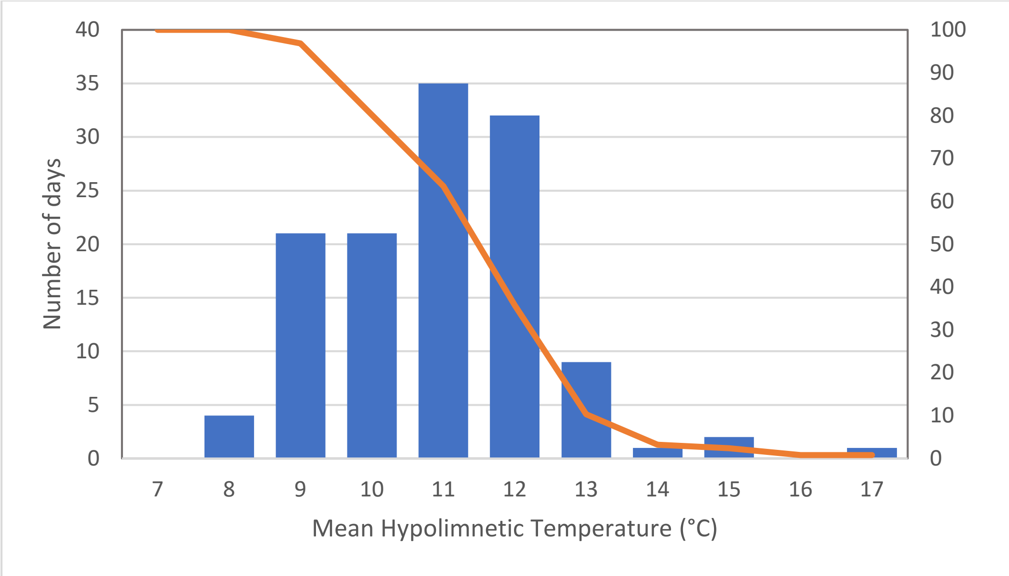

Figure 9. Frequency distribution of mean hypolimnetic temperatures each date there was a temperature profile taken at the deep hole of the East Basin. Only dates from July 13 to September 14 were included as this is the time period when whitefish OLT was sometimes <1 m. Blue bars show the number of dates at each mean hypolimnetic temperature. The orange line shows the cumulative percent of dates that exceed a given mean hypolimnetic temperature from high to low temperatures (right vertical axis).

Examining a potential relationship between oxythermal habitat and phosphorus

To better establish a connection between the oxythermal layer thickness and phosphorus directly, first OLT must be controlled for its response to temperature. This re-analysis includes a set of models that detrend temperature from OLT to isolate the effect of phosphorus (including all stations simultaneously to make the best use of the available data). Several predictor variables that describe temperature were included in a multivariate regression model to test for the strength of their relationship to OLT (Table 3). Temperature predictors were tested for both air temperature and water temperature. The two variables with the highest correlation coefficients were selected for inclusion in the model. Growing degree days (GDD) and mean epilimnetic temperature (T_e) had the strongest relationship with OLT. Both temperature metrics, as well as mean annual TP were included in a linear regression model. After controlling for temperature, the residual variance regressed against TP can be considered the isolated effect of TP on OLT.

Table 3. Candidate predictor variables for controlling for the effect of air and water temperature (T_a, T_w) on oxythermal layer thickness (OLT), and isolating the effect of total phosphorus (TP), with their correlation coefficient (r) against OLT.

Predictor Variables		**r**
Air temperature, T_a	day of year	-0.67
	maximum daily temperature	-0.36
	minimum daily temperature	-0.34
	growing degree days (base 0)	-0.68
Water temperature, T_w	thermocline depth	-0.26
	surface temperature	-0.68
	epilimnetic mean temperature	-0.72
	temperature at thermocline	-0.52
	metalimnetic mean temperature	-0.53
	hypolimnetic mean temperature	-0.52
	temperature at bottom	-0.49
TP	Annual mean	-0.09
	Annual mean of last 2 years	-0.19
	Annual mean of last 3 years	-0.19
	Annual mean of last 4 years	-0.21

The 2018 TSD (WDNR, 2018) looked at individual effects of TP on OLT and HOD, both in terms of the physical processes (e.g., temperature, phosphorus), and in terms of each of the three basins in the lake. To make better use of the data available, this re-analysis looked at combined physical factors as well as all stations combined in a single model. To assess all these factors in a single, global model, we tested various linear mixed effects model using monitoring station as a random effect on the intercept (Bates, 2014). In other words, a global model was fit for slopes on all fixed effects (e.g., GDD, T_e, and TP), while the intercept could vary across each monitoring station. This approach substantially increased the amount of information that can be assessed simultaneously, without limiting the ability to make site-specific predictions. However, even with the increased statistical power, a significant relationship between TP and OLT could not be found.

The general model took the form of the following formula, using R lme4 notation (Bates, 2014) where S is the monitoring station random effect:

Equation 3

$$OLT \sim T_a + T_w + TP + (1|S)$$

where T_a and T_w are one of the air and water temperature metrics found in Table 3. Different combinations of T_a and T_w were tested, and the combination of GDD (T_{base} = 0°C) and epilimnetic temperature (T_e) were found to be the best predictors of OLT, resulting in 76% of the variance explained by the model (conditional R^2 using both fixed and random effect on monitoring station). The following table (Table 4) describes the various models that were tested, and whether the addition of a TP co-variate improved the model based on the p-value of an ANOVA chi-squared test.

Table 4. Model diagnostics testing for model improvement after adding phosphorus as a co-variate to predict Oxythermal Layer Thickness (OLT) using ANOVA X^2 test (< 0.05 indicates a significant improvement), and change in Information Criteria (Akaike, ΔAIC, and Bayesion, ΔBIC, negative values indicate an increase after adding TP). Annual average growing-season total phosphorus (TP), and a lagged version that included averages across multiple prior years (TP_{1-3}), were used to test for the effect of TP on OLT. After including each TP metric, and testing for the effect of TP, using OLT calculations associated with both lake whitefish and cisco thermal limits (18.9°C and 22.8°C), no association between TP and OLT was observed with the available data.

TEMPERATURE MODEL	MODEL INCLUDING TP METRIC	SPECIES	ΔAIC	ΔBIC	p
OLT ~ T_e + GDD + (1|S)	OLT ~ T_e + GDD + TP + (1|S)	Whitefish	0.11	-2.87	0.15
	OLT ~ T_e + GDD + TP_1 + (1|S)	Whitefish	-1.08	-4.06	0.34
	OLT ~ T_e + GDD + TP_2+ (1|S)	Whitefish	-0.89	-3.87	0.29
	OLT ~ T_e + GDD + TP_3+ (1|S)	Whitefish	0.23	-2.75	0.14
	OLT ~ T_e + GDD + TP + (1|S)	Cisco	-1.03	-4.01	0.32
	OLT ~ T_e + GDD + TP_1 + (1|S)	Cisco	-1.95	-4.96	0.88
	OLT ~ Te + GDD + TP_2+ (1|S)	Cisco	-1.95	-4.94	0.83
	OLT ~ Te + GDD + TP_3+ (1|S)	Cisco	-1.39	-4.37	0.44

The above demonstration shows that, although an embedded process that relates phosphorus to cisco and whitefish habitat may exist in LCO, the available data and compilation of predictor variables do not show a connection. Therefore, even with this more robust statistical analysis including additional predictors, no direct link was found that connects OLT with TP in LCO. Although this component of the analysis did not provide actionable information, it is documented here for completeness. While this component of the analysis does not provide additional support for the proposed criterion of 10 ug/L, the analyses detailed in the earlier sections of this document do provide a scientific basis for the recommendation of a criterion of 10 ug/L phosphorus to better support whitefish survival.

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Lac Courte Oreilles, Sawyer County Phosphorus Site-Specific Criteria Analysis

WDNR Technical Support Document

Final 2-23-2018

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Table of Contents

1. Summary of Findings & Recommendations

DNR undertook an analysis to assess whether a site-specific phosphorus criterion (SSC) is appropriate for Lac Courte Oreilles and its bays, and if so, at what value it should be set. Lac Courte Oreilles, including its small bays, is subject to the statewide phosphorus water quality criterion for stratified, two-story fishery lakes, 15 micrograms per liter (µg/L) of total phosphorus (TP). Musky Bay is subject to the statewide phosphorus criterion for unstratified drainage lakes, 40 µg/L TP. Both resources are currently attaining the statewide phosphorus criteria, but there are water quality concerns related to both fish habitat and recreation. Data suggest that coldwater fish habitat is impacted by limitations of the "oxythermal layer" within which those species can survive. Because of this, in 2018 the main basins of Lac Courte Oreilles are proposed for listing as impaired based on not attaining the designated cold water aquatic life use due to low dissolved oxygen. Low dissolved oxygen can be caused by a number of factors, including high concentrations of phosphorus within a waterbody. Under these circumstances, Wis. Adm. Code s. NR 102.06(7) authorizes DNR to evaluate the waterbody and consider whether a different phosphorus criterion—an SSC—is necessary to be protective of the waterbody's designated uses.

In order to establish a more-stringent phosphorus SSC, we must demonstrate 1) the designated uses are not protected by the statewide phosphorus criterion, 2) a clear link between phosphorus concentrations and protection of these designated uses, and 3) that scientific evidence demonstrates that a more-stringent phosphorus concentration is necessary to protect the designated uses. Therefore, any SSC for Lac Courte Oreilles must be based on protection of the lake's designated uses, which are measured using several biological metrics as shown in Table 1. After assessing each of these metrics and further investigating root causes of the oxythermal limitations, we find that the deficiency in the coldwater fishery habitat is not clearly driven by phosphorus. We also find that other phosphorus response metrics are attained, even though average phosphorus concentrations are approaching the statewide numeric phosphorus criterion. Because current levels of phosphorus are not clearly driving the habitat deficiency, setting a more-stringent SSC than 15 µg/L is not appropriate for the main basins of Lac Courte Oreilles. Additionally, there is no technical basis to assign a separate criterion for the small bays of Lac Courte Oreilles.

Within Musky Bay, although there have been observed concerns related to nutrients, the standard phosphorus response metrics that the department assesses—chlorophyll *a* and the aquatic plant community—are currently not showing impairment. We recommend maintaining the statewide criterion of 40 µg/L for Musky Bay. While Musky Bay was listed as impaired for invasive plants and phosphorus in 2012, data from 2012 to 2017 indicate that all parameters have improved and are currently attaining thresholds.

Our main findings are as follows.

Main basins (West, East, Central)

Phosphorus

- The total phosphorus (TP) means for all main basins currently attain the applicable criterion of 15 µg/L. Mean TP for the basins are 13.68 µg/L (West Basin), 12.32 µg/L (Center Basin), and 12.10 µg/L (East Basin).
- TP significantly increased in the East Basin since the beginning of our records in 1988. TP has not significantly changed over time in the West Basin or Center Basin, but the period of record is shorter in these basins.

All phosphorus criteria must be set to be protective of the resource's designated uses. The aquatic life designated use of Lac Courte Oreilles' main basins is coldwater (stratified two-story fishery), and the aquatic life designated use of Musky Bay is warmwater. For assessing the recreation use, the main basins are categorized as stratified (deep) drainage lakes, and Musky Bay is categorized as an unstratified (shallow) drainage lake. DNR used the following biological metrics to evaluate whether the statewide phosphorus criterion is protective of these uses. These metrics and related thresholds are currently included in proposed rule packages WT-23-13 and WY-25-13.

Chlorophyll *a*

- All three basins attain the aquatic life chlorophyll *a* threshold for stratified two-story fishery lakes (attained if <10 µg/L). Mean chlorophyll *a* values for the basins are approximately 2 µg/L at each basin.
- All three basins attain the recreation chlorophyll *a* threshold for stratified drainage lakes (attained if <5% of summer days have moderate algae levels). Each basin has zero percent of summer days with moderate algae levels.
- Therefore, TP does not need to be reduced from current concentrations in the main basins to protect for the recreation and aquatic life uses as determined by chlorophyll *a* metrics.
- Chlorophyll *a* has not changed significantly over time in any of the main basins.

Aquatic plants

Aquatic plant thresholds for Northern drainage lakes were applied for both the general condition assessment (attained if tolerant species $\leq$73%) and the phosphorus response assessment (attained if phosphorus-sensitive species are >51%).

- An aquatic plant survey conducted in August, 2010 shows that the whole-lake plant community is healthy. The plant community attains the general condition threshold used to assess for response to a range of disturbances, with tolerant species present at 27% of sampling points. It also attains the threshold that would indicate a response specific to phosphorus, with phosphorus-sensitive species present at 87% of sampling points.
- Therefore, TP does not need to be reduced from current concentrations in the main basins to protect the aquatic plant community.

Two-story fishery oxythermal habitat for cisco & whitefish

Because Lac Courte Oreilles is a two-story fishery lake, meaning it supports a coldwater fishery, the oxythermal habitat thresholds for cisco and whitefish are applied. Cisco and whitefish need a layer of water that is both cold enough and has enough dissolved oxygen for them to survive. This is called the "oxythermal layer" and is measured using "oxythermal layer thickness" (OLT). During the late summer, this layer can become compressed/reduced to such an extent that it does not provide enough habitat for coldwater fish to survive, and may stress or kill fish. To attain the OLT threshold, a lake must have at least 1 meter of depth at which dissolved oxygen is above 6 mg/L and water temperature is 66°F (18.9°C) or colder for whitefish or 73°F (22.8°C) for cisco.

- None of the three basins attains the OLT threshold for whitefish, the more sensitive of the two species. The cisco threshold is attained in all basins over the past five years, but is not attained in the West Basin if earlier years are considered.
- Habitat for whitefish has been marginal since the beginning of our data records (1975), and the OLT has not declined over that period of time. This finding suggests that the whitefish population in Lac Courte Oreilles may be supported by immigration from Whitefish Lake.

Causes of negative impacts to coldwater fish through compression of the oxythermal layer

Habitat for coldwater fish can be limited by warming temperatures near the surface and by oxygen depletion in the deep, cold water. We evaluated five potential causes of negative impacts to coldwater fish habitat and their relationship to phosphorus. **Through this analysis, 1) we determined that factors other than phosphorus are likely to be impacting the oxythermal layer; and 2) we were unable to verify that phosphorus concentrations and related processes were negatively impacting the oxythermal layer. Therefore we could not conclude that a site-specific phosphorus criterion is necessary to protect aquatic life uses in the main basins.**

1) Decomposition of organic matter in the water column

- This is a small component of total Hypolimnetic Oxygen Demand (HOD) in Lac Courte Oreilles.
    - Concentrations of chlorophyll *a* in the water column are low.
    - Tests of oxygen demand from sediment cores from Lac Courte Oreilles indicate that more than half of total HOD comes from aerobic decomposition of organic matter in the sediment. This means that less than half of HOD comes from decomposing organic matter in the water column.
- Reducing phosphorus concentrations is unlikely to reduce HOD.
    - The relationship between phosphorus concentrations and HOD was non-existent in the West and Central Basins and was variable in the East Basin.
    - In the East basin, phosphorus has increased over time, but HOD has not.
    - In the West basin, one measure of HOD increased over time, but phosphorus has not.
    - HOD has been high enough to eliminate the oxythermal layer even in years with phosphorus concentrations as low as 7 µg/L.
    - In the LimnoTech analysis, a model developed by Chapra and Canale (1991) was used to propose an SSC of 10 µg/L TP. However, this model is not an appropriate method for determining a site-specific phosphorus criterion for Lac Courte Oreilles. A relationship observed across lakes as in the Chapra and Canale study will not necessarily hold true within a single lake. In Lac Courte Oreilles, HOD is higher for a given phosphorus level than in other lakes and does not show a similar decline in HOD with declining phosphorus.

2&3) Aerobic decomposition of sediment organic matter

- This is a large component of HOD.
    - A laboratory study of sediment cores, though not an exact measure of in-lake dynamics, estimates that this accounts for 59% of HOD in the East Basin, 92% in the Central Basin, and 75% in the West Basin.
    - Previous studies report high organic matter content in the sediments.
- The influence of phosphorus on accumulation of sediment organic matter is uncertain.
    - Further studies are needed to determine the current sedimentation rate and whether the organic matter mostly comes from within the lake or from land.
        - If future studies determine the organic matter mostly comes from algal production in the lake, then reducing phosphorus concentrations would reduce the influence of organic matter decomposition on HOD over time.
        - If sediment organic matter mostly comes from land, management options for reducing external inputs should be examined. Reducing phosphorus would not be effective.

4) Oxidation of reduced substances in the sediment

- A portion of HOD is caused by the oxidation of reduced substances, such as methane, ammonium, nitrite, manganese, iron, or sulfide. Further study is needed to quantify how much these processes contribute to oxygen reduction.

- Given Lac Courte Oreilles's hypolimnetic thickness (z) of 7.8 m and a comparison to other lakes, reduced substances could account for 50-75% of Areal Hypolimnetic Mineralization (AHM). This means that oxygen consumption is likely even higher than estimated using HOD (oxygen consumption = HOD plus oxidation of reduced substances).
- All three basins have high iron levels in the sediment. Additionally, limited data found high concentrations of iron in the hypolimnion of the West Basin with an increase over the summer season (up to 8 mg/L), providing evidence that oxidation of at least one reduced substance is occurring in Lac Courte Oreilles. The other two basins had much lower iron concentrations in the hypolimnion.
- Reducing phosphorus will not affect oxidation of reduced substances.

5) Warming surface water temperatures

- Historically, a large portion of the OLT occurred in the epilimnion. The epilimnion was often cold enough to provide suitable habitat for coldwater fish even in late summer, but since 1975 epilimnetic and surface water temperatures have increased by 1.7 and 2.15°C, respectively. There is no long-term trend in water temperature in the lower layers of the lake (thermocline, hypolimnion, or bottom).
- If the warming trends continue, future warming will further exacerbate thermal stress for cisco and whitefish.
- Reducing phosphorus will not reduce water temperature.

Conclusions for the main basins
We do not recommend an SSC for the main basins of the lake, and instead recommend retaining the statewide TP criterion of 15 µg/L. This recommendation is based on the following line of reasoning.

Is phosphorus clearly causing the negative impacts to the coldwater fish community?

- ➔ **No.** Our analyses cannot verify that phosphorus is reducing the oxythermal layer and there are several plausible alternative factors not related to phosphorus that could be causing the negative impacts. Further research is recommended to better understand the mechanisms of oxygen depletion, which will help guide efforts to improve the two-story fishery habitat.

Would a phosphorus concentration lower than the statewide criterion of 15 µg/L reduce the negative impacts to the oxythermal layer and coldwater fishery?

- ➔ **Probably not.** Phosphorus concentrations ranged from 6.3 – 14.7 µg/L over the period of record, and HOD was unchanged. Even in the East Basin where there was a significant relationship between one measure of HOD and TP, HOD could be as high at 8 µg/L TP as at 14.7 µg/L TP. Given the additional causes of two-story fishery impacts described above, reduced phosphorus is not likely to significantly improve the two-story fishery habitat deficiencies.

Small Bays (other than Musky Bay)

Small bays are not assigned separate designated uses from the main lake, unless they are significantly restricted from the main lake and exhibit different characteristics (such as Musky Bay, discussed below). Although small bays would not typically be assessed separately from the main basins, we applied the same methodology to review the limited data available from Stuckey Bay, Chicago Bay, Anchor Bay, Northeast Bay, and Brubaker Bay for informational purposes.

Phosphorus

- Total phosphorus was low in all four bays with data: Anchor Bay, Northeast Bay, Stuckey Bay, and Chicago Bay. Their mean phosphorus concentrations, ranging from 10.41 to 13.51, are lower than any of the statewide phosphorus criteria. There was not any data from Brubaker Bay.
- Annual average TP has not significantly changed over time in any of the bays. Note that TP in Stuckey Bay was high in 2000.

Chlorophyll *a*

- Chlorophyll *a* was low in all four bays with data: Anchor Bay, Northeast Bay, Stuckey Bay, and Chicago Bay. Each small bay has zero percent of days with moderate algae levels. Mean chlorophyll *a* for each of the small bays was ~2 µg/L. These are lower than any of the statewide chlorophyll *a* thresholds for aquatic life or recreation uses. There was not any data from Brubaker Bay.
- Therefore, TP does not need to be reduced from current concentrations in the small bays to protect for the chlorophyll *a* recreation and aquatic life uses as determined by chlorophyll *a* metrics..
- Chlorophyll *a* did not change significantly over time in any of the small bays.

Aquatic plants

The 2010 plant survey was used to assess the individual bays. Although this provides a somewhat limited dataset for each unit, the results for the bays are similar to those for the whole lake. Aquatic plant thresholds for Northern drainage lakes were applied for both the general condition assessment (attained if tolerant species ≤73%) and the phosphorus response assessment (attained if phosphorus-sensitive species are >51%).

- The plant community in each of the five bays attains the general condition threshold used to assess for response to a range of disturbances, with tolerant species present from 9 to 50% of sampling points in the various bays. It also attains the threshold that would indicate a response specific to phosphorus, with phosphorus-sensitive species present at 83-97% of sampling points in the various bays.
- Therefore, TP does not need to be reduced from current concentrations in the small bays to protect the aquatic plant community.

Conclusions for small bays

There is no technical basis to assign a separate criterion for the small bays of Lac Courte Oreilles. We do not recommend that a phosphorus criterion be applied to the small bays that is different from the overall lake, for two main reasons:

- Standardized methods for assessing health of small bays independent from the overall lake are not yet available, and methods for developing appropriate criteria for small bays are also unavailable.
- Each of the four small bays with data exhibit very low chlorophyll levels, attaining even the most stringent thresholds, and a healthy aquatic plant community. There is no justification for treating these bays differently from bays on other lakes in the state.

As a general matter, the criterion applied to the main basins in a lake should be considered inclusive of the small bays, whether that be the statewide criterion or an SSC. Assessment of that criterion should follow standard protocols for all lakes, using measurements only at the deep hole(s), not samples within the small bays. In this case, the statewide phosphorus criterion for Lac Courte Oreilles is protective of the designated uses of the lake, and therefore also protective of the small bays.

Musky Bay

Because Musky Bay is significantly restricted from the main lake and exhibits different physical characteristics, it is considered an unstratified (shallow) drainage lake for purposes of supporting both the warmwater aquatic life use and recreation use.

Phosphorus

- Musky Bay's summer mean phosphorus concentration is 29.53 µg/L, which attains the currently applicable TP criterion of 40 µg/L.
- Musky Bay's annual average TP does not exhibit a significant trend over time when looking at the entire data record from 2000 to 2017. However, prior to 2010 TP was more variable and exceeded the criterion in some years. After 2012, TP was less variable and declined through 2017.

DNR used the following biological metrics to evaluate whether the statewide phosphorus criterion is protective of Musky Bay's warmwater aquatic life and recreation designated uses. These metrics and related thresholds are currently included in proposed rule packages WT-23-13 and WT-25-13.

Chlorophyll *a*

- Musky Bay attains the chlorophyll *a* thresholds for recreation and aquatic life for unstratified drainage lakes. Musky Bay's mean chlorophyll *a* concentration is 5.75 µg/L (attained if <27 µg/L). It has ~6% of summer days with moderate algae levels (attained if <25% of summer days have moderate algae levels).
- Chlorophyll *a* was still well below the threshold in years when TP exceeded the current criterion applied to Musky Bay of 40 µg/L.
- Therefore, 40 µg/L TP is protective of both the recreation and aquatic life chlorophyll *a* metrics.
- Chlorophyll *a* in Musky Bay did not exhibit a significant trend over time, though it did fluctuate over time with changing TP concentrations.
- Chlorophyll *a* is higher in Musky Bay than elsewhere in Lac Courte Oreilles.

Aquatic plants

- Plant data collected with high spatial resolution in Musky Bay in 2007 and in all years 2010 – 2016 revealed that Musky Bay attained the general condition threshold in all years (attained if tolerant species ≤73%). In 2011 and 2012, it failed to attain the plant phosphorus response threshold (attained if phosphorus-sensitive species >51%), indicating there may have been a short-term impairment that could be related to nutrient levels. Since then (2013-2016), plants consistently attained the phosphorus response thresholds.
- The available data suggest that 40 µg/L is protective of aquatic plants in Musky Bay. Three aquatic plant surveys attained the phosphorus response indicator when phosphorus was 32.7 – 38.0 and two aquatic plant surveys did not when phosphorus was 37.1 - 41.6 µg/L.
- Musky Bay was listed as impaired for high densities of curly-leaf pondweed, an invasive aquatic plant, in 2012. The number of acres treated with herbicide has declined in recent years, suggesting that curly-leaf pondweed is not as pervasive as it was in 2010-2012. The curly-leaf pondweed population likely responds to the combined influence of a large number of environmental variables, and we currently lack sufficient understanding of the relationship between curly-leaf pondweed biomass and water column nutrient concentration to use curly-leaf pondweed density as an indicator of nutrient impairment. In addition, the active management of curly-leaf pondweed may hamper our ability to discern the specific relationship between environmental factors and the present population.

- The density and biomass of aquatic plants and their relationship with phosphorus could not be evaluated with available data or methods.

Paleolimnological information

- Prior sediment core studies indicate nutrient enrichment has been occurring since the 1930s. Periods in the 1960s, 1970s, and late 1990s also contributed to nutrient enrichment in the lake.
- Natural background concentrations of TP are estimated at 19 and 29 µg/L TP, based on two sediment core analyses, but these estimates are approximate. The natural background concentration represents the lowest level at which an SSC might be set.

Conclusions for Musky Bay

- We do not recommend setting a site-specific phosphorus criterion lower than the applicable statewide criterion of 40 µg/L for Musky Bay. Available data include a range of phosphorus concentrations in Musky Bay that allows us to directly observe how it responds to high phosphorus concentrations. Our existing assessment methods showed that when phosphorus was greater than 40 µg/L, chlorophyll *a* still indicated healthy conditions. The available data, though limited, suggest that 40 µg/L is protective of aquatic plants as well. Three aquatic plant surveys attained the phosphorus response indicator when phosphorus was 32.7 – 38.0 and two aquatic plant surveys did not when phosphorus was 37.1 and 41.6 µg/L.
- We recommend delisting Musky Bay from the impaired waters list. In 2012, when Musky Bay was listed for high curly-leaf pondweed abundance with phosphorus as the pollutant, both TP and the plant metrics indicated that the lake was impaired. Now, at 29.53 µg/L, TP clearly attains the criterion of 40 µg/L. Treatment for curly-leaf pondweed has been effective in reducing its presence. Chlorophyll *a* attains both the recreation and aquatic life thresholds, and aquatic plants indicate that Musky Bay is in good condition.
- If observation or additional information indicate that spawning habitat for muskies, algal mats, and aquatic plant biomass are still problematic in Musky Bay, we recommend developing a monitoring program that quantifies these stress signals. In addition, phosphorus and other potential factors should be monitored at the same time to determine if there is a link between phosphorus and each of these variables. A cross-lake comparison and review of the literature may also help to establish expectations for each of these variables and their relationship to phosphorus.

2. BACKGROUND

Lac Courte Oreilles is a lake in Sawyer County near Hayward (Figure 1). The lake straddles state land and Tribal lands of the Lac Courte Oreilles Band of the Lake Superior Chippewa (the Tribe). The lake has three major basins, West, Central, and East; a large bay called Musky Bay that is somewhat restricted from the rest of the lake; and several small bays along the shoreline of the major basins (Figure 2). The lake is listed as a state Outstanding Resource Water. Because of the presence of two coldwater fish species, cisco and whitefish, the majority of the lake is classified by the department as a two-story fishery lake. Musky Bay, because of its shallow nature and restriction from the deeper portions of the lake, is classified as a shallow lowland drainage lake.

Lac Courte Oreilles has a long record of sampling by Wisconsin Department of Natural Resources (WDNR) staff, Tribal staff, and the Courte Oreilles Lake Association (COLA). There is strong local interest and a history of active participation in managing the lake and watershed to protect the fishery, manage invasive species, and support recreation uses.

In 2012, the department listed Musky Bay on Wisconsin's Clean Water Act 303(d) impaired waters list for total phosphorus, water quality use restrictions, and non-native aquatic plants. This was due to exceedances of the phosphorus criterion preceding that time and observed macrophyte density causing impairment of recreation. The majority of the macrophytes were curly-leaf pondweed, an invasive species. The main portion of Lac Courte Oreilles is not listed for total phosphorus because assessments have not shown an exceedance of Two-Story Fishery phosphorus criterion. During the 2018 assessment cycle, an assessment of habitat for coldwater fish species based on dissolved oxygen and temperature showed that the main portion of Lac Courte Oreilles is not attaining the department's proposed oxythermal criteria for two-story fishery lakes. During 2015 and 2016, the main basins experienced fish kills associated with depleted oxygen. The lake is currently proposed for the 2018 impaired waters list for impacts to the coldwater aquatic life designated use due to low dissolved oxygen. As discussed in this document, causes of the reduction of the oxythermal layer are unknown.

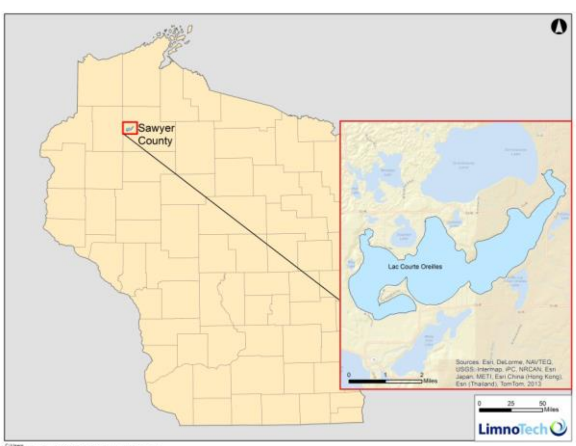

Figure 1. Location of Lac Courte Oreilles within Wisconsin.

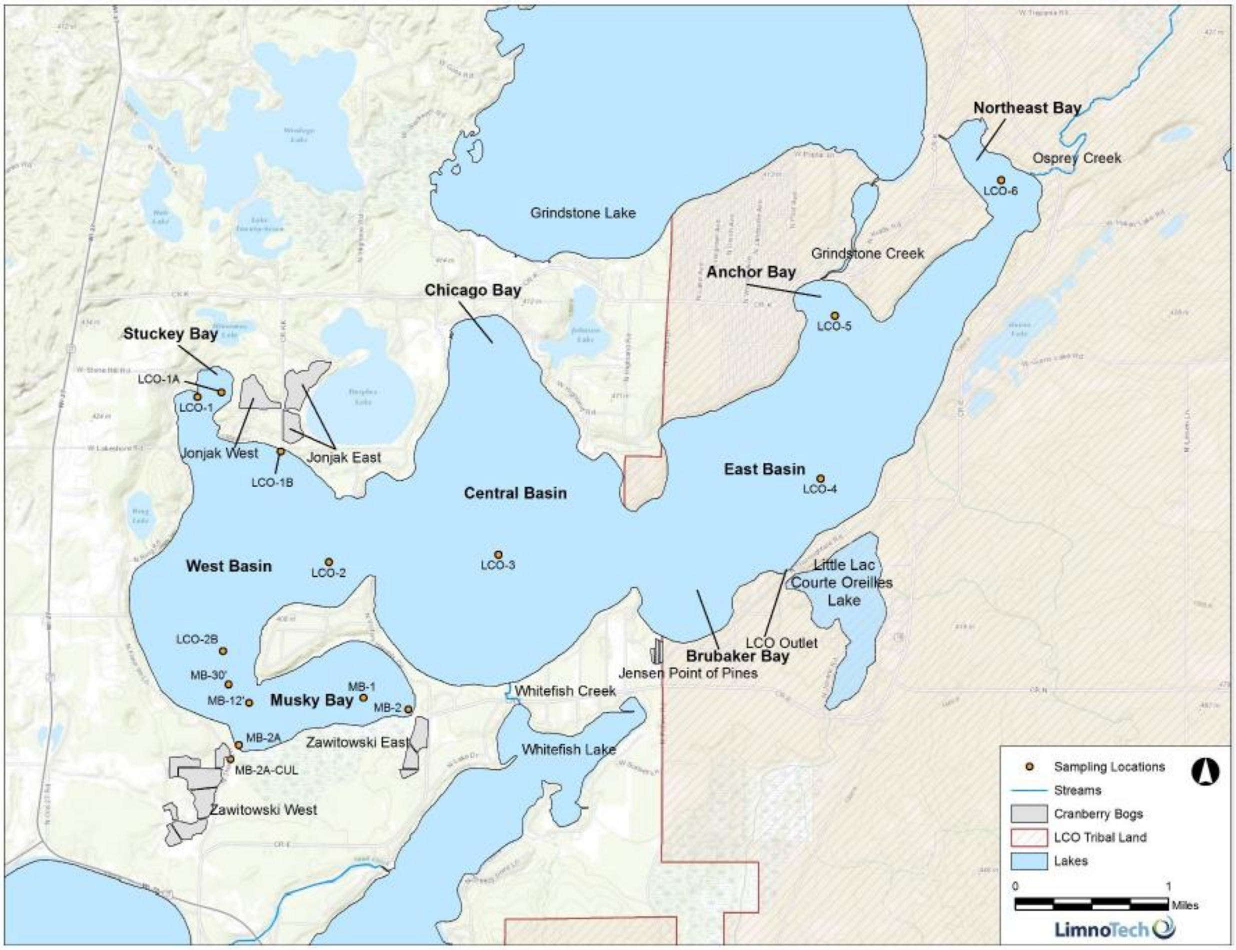

Figure 2. Lac Courte Oreilles map showing tributaries, major basins and bays, sampling stations, Lac Courte Oreilles Band of Lake Superior Chippewa Tribal land, and cranberry bog locations. Source: LimnoTech, 2016.

2.1 Court settlement on Lac Courte Oreilles site-specific criteria for phosphorus

In 2014 COLA and the Tribe submitted to DNR for consideration a proposed site-specific criterion of 10 µg/L TP to DNR for Lac Courte Oreilles and Musky Bay (LimnoTech, 2014a), along with a proposed Total Maximum Daily Load (TMDL) analysis (LimnoTech 2014b). DNR reviewed the submitted materials but declined to make a determination on them at that time because DNR was in the midst of a larger, ongoing rulemaking effort to establish a standard process for developing SSC that would be applicable to SSC cases statewide. DNR planned to complete that effort before undertaking development of SSC for individual waterbodies. That rulemaking process is still ongoing.

In March 2016, COLA and the Tribe (the petitioners) submitted to WDNR a petition for rulemaking, seeking an SSC for phosphorus in Lac Courte Oreilles. In May 2016, DNR denied that petition. In June 2016, petitioners filed a petition for judicial review asking a court to review WDNR's decision not to promulgate phosphorus SSC for Lac Courte Oreilles. At that time, the petitioners submitted an updated SSC proposal document (LimnoTech, 2016), again recommending a SSC of 10 ug/L TP. In a court-approved settlement filed on April 4, 2017: Case No. 16-CV-1564 (Admin. Agency Review 30607), *James Coors, et. al., v. Wisconsin Department of Natural Resources and Wisconsin State Cranberry Growers Association*, the

WDNR agreed to "propose a phosphorus SSC for Lac Courte Oreilles, inclusive of the East, Central, and West Basins and Stuckey Bay, Musky Bay, Chicago Bay, Brubaker Bay, Anchor Bay, and Northeast Bay, as authorized by Wis. Admin. Code s. NR 102.06(7)" and to "propose a scope statement for the development of a proposed phosphorus SSC for Lac Courte Oreilles." The parties to this case include James Coors on behalf of the Courte Oreilles Lakes Association, Inc. (COLA), the Lac Courte Oreilles Band of Lake Superior Chippewa (Tribe), the Wisconsin Department of Natural Resources (WDNR) and Natural Resources Board, and the Wisconsin State Cranberry Growers Association as intervenors.

In accordance with the court-approved settlement and consistent with the authority provided in Wis. Admin. Code § NR 102.06(7), DNR developed a scope statement to evaluate a potential SSC for Lac Courte Oreilles through the rulemaking process established in Wis. Stat. ch. 227. The Governor's Office and Natural Resources Board approved the scope statement. In accordance with the scope statement and Wis. Admin. Code § NR 102.06(7), DNR proceeded to evaluate the information in the petitioners SSC proposal and existing information and data concerning the lake. DNR also collected new data and information and incorporated those findings into its evaluation of whether an SSC is warranted. As described above, the data indicate that phosphorus concentrations in the lake are not the main driver impacting two-story fishery habitat, and therefore a more stringent SSC cannot be verified as necessary to attain the applicable designated uses.

3. Basis for Site-Specific Criteria

3.1 Regulatory authority

A site-specific criterion is established for an individual waterbody or segment when the statewide criterion is either over- or under-protective to support the designated uses of the waterbody due to site-specific characteristics. The authority for adopting any water quality criteria is established in Wis. Stat. s. 281.15:

> **(1)** The department shall promulgate rules setting standards of water quality to be applicable to the waters of the state, recognizing that different standards may be required for different waters or portions thereof. Water quality standards shall consist of the designated uses of the waters or portions thereof and the water quality criteria for those waters based upon the designated use. Water quality standards shall protect the public interest, which include the protection of the public health and welfare and the present and prospective future use of such waters for public and private water systems, propagation of fish and aquatic life and wildlife, domestic and recreational purposes and agricultural, commercial, industrial and other legitimate uses. In all cases where the potential uses of water are in conflict, water quality standards shall be interpreted to protect the general public interest.

The statute further states:

> **(2)** In adopting or revising any water quality criteria for the waters of the state or any designated portion thereof, the department shall do all of the following:
>
> **(c)** Establish criteria which are no more stringent than reasonably necessary to assure attainment of the designated use for the water bodies in question.

This provides sideboards specifying that criteria cannot be set more stringent than can be justified as necessary to attain designated uses. Therefore, to establish a water quality criteria DNR must demonstrate that there is a clear link between the substance in question and attainment of a designated use.

Wisconsin Administrative Code also specifically allows for the development of phosphorus site-specific criteria under Wis. Adm. Code s. NR 102.06(7):

> **NR 102.06 Phosphorus.** (7) SITE-SPECIFIC CRITERIA. A criterion contained within this section may be modified by rule for a specific surface water segment or waterbody. A site-specific criterion may be adopted in place of the generally applicable criteria in this section where site-specific data and analysis using scientifically defensible methods and sound scientific rationale demonstrate a different criterion is protective of the designated use of the specific surface water segment or waterbody.

In accordance with the administrative code, DNR is to use its technical expertise to determine if the statewide phosphorus criterion should be modified to protect the designated uses. The code authorizes DNR to use its discretion to establish an SSC if scientific data supports the decision.

Therefore, in order to establish a more-stringent phosphorus SSC, we must demonstrate 1) the designated uses are not protected by the statewide phosphorus criterion, 2) a clear link between phosphorus concentrations and the protection of these designated uses, and 3) that scientific evidence demonstrates that a more-stringent phosphorus concentration is necessary to protect the designated uses.

3.2 Applicable designated uses

As specified above in Wis. Stat. s. 281.15 and Wis. Adm. Code s. NR 102.06(7), a site-specific criterion may be set to be protective of the designated use(s) of the waterbody in question. All surface waters are assigned the following four designated uses: Fish and Aquatic Life (hereafter Aquatic Life), Recreation, Wildlife, and Public Health and Welfare. For purposes of this analysis, only aquatic life and recreation are assessed because the state's phosphorus criteria are not applicable to the wildlife or public health and welfare uses.

The aquatic life designated use has the following subcategories: coldwater, warmwater sport fish, warm water forage fish, limited forage fish, and limited aquatic life. With the exception of Musky Bay, Lac Courte Oreilles has a designated aquatic life use of "Cold water community" ("coldwater"). Chapter NR 102.04(3)(a) states: "This subcategory includes surface waters capable of supporting a community of cold water fish and other aquatic life, or serving as a spawning area for cold water fish species." Lac Courte Oreilles supports cisco and whitefish, two coldwater species. The department is currently proposing rule revisions to the designated uses section of ch. NR 102.04(3) that would further specify that that stratified two-story fishery lakes receive a coldwater designated use. Existing code language in s. NR 102.06(2)(i) defines a "stratified two-story fishery lake" as "a stratified lake which has supported a cold water fishery in its lower depths within the last 50 years." Lac Courte Oreilles falls within that definition.

Small bays are not assigned separate designated uses from the main lake, unless they are significantly restricted from the main lake and exhibit different characteristics (such as Musky Bay, discussed below). For purposes of this analysis, Stuckey Bay, Chicago Bay, Anchor Bay, Northeast Bay, and Brubaker Bay are covered under the same uses and metrics as shown here for the main lake, except that the oxythermal habitat threshold proposed in the rule revision would not apply as these portions of the lake do not stratify.

Musky Bay is significantly different in characteristics from the main, deep (stratified) portion of the lake. Musky Bay is adjacent to the West Basin but is restricted from the main lake by a natural narrow channel.

Musky Bay is a shallow system that does not contain coldwater habitat, and the department applies the "Warm water sport fish community" ("warmwater") designated use to this portion of the lake.

3.3. Water quality criteria applicable to designated uses

Water quality criteria are developed by the state to support each designated use. Many criteria are divided into subcategories for different types of waterbodies, employing finer distinctions than the more general designated use categories. Each criterion may need its own subcategories because different types of waterbodies respond differently to each pollutant, or have different biological characteristics beyond just 'cold' versus 'warm'. Criteria are developed that are appropriate for each subcategory.

For each portion of Lac Courte Oreilles, Table 1 shows the applicable designated uses, metrics and their subcategories, criteria or thresholds, and where those criteria or thresholds are documented (existing code, WisCALM guidance, or proposed code revisions).

Proposed phosphorus response indicators and biocriteria

Separately from the development of an SSC for Lac Courte Oreilles, the department is currently proposing several revisions and additions to ch. NR 102, Wis. Adm. Code, which would apply to waterbodies statewide. These include adding both "biocriteria" and "phosphorus response indicators". Biocriteria are metrics indicating the overall health of a waterbody. Phosphorus response indicators are metrics that specifically indicate a response to phosphorus. Both are used to evaluate whether designated uses are being protected. The proposed metrics include the following that are relevant here:

- Proposed chlorophyll *a* criteria for both aquatic life and recreation uses
    - The chlorophyll *a* thresholds are currently in use through Wisconsin's waterbody assessment guidance: Wisconsin Consolidated Assessment and Listing Methodology (WisCALM)
- Proposed aquatic plant criteria to assess both general disturbance responses and phosphorus-specific responses
- Proposed oxythermal habitat criteria to protect two-story fishery lakes

Within this document, the term "criterion" is used for an existing, codified criterion (such as total phosphorus), and the term "threshold" is used for the above metrics being proposed for codification in the rule revisions to ch. NR 102 (as per the January 2018 draft rule), but which are not yet criteria.

For Lac Courte Oreilles, WDNR used the proposed phosphorus response indicators and biocriteria thresholds to assess the need for an SSC (shown in Table 1). Under the proposed rule revisions as applied in this analysis, if any of the thresholds are not attained and a lower phosphorus criterion is needed to attain them, then a more-stringent SSC may be appropriate. The SSC value would then be set at the phosphorus concentration needed to attain the biological metrics that demonstrate support of the designated uses.

Table 1. Designated uses, metrics, and criteria applicable to portions of Lac Courte Oreilles.

Portion of the lake	Designated Use**	Metrics supporting the Designated Use	Metric subcategory	Applicable criterion or threshold (attains if…)	Source of the criterion or threshold
Main basins* (West, Central, East)	Aquatic Life: Coldwater	Total Phosphorus	Two-story fishery	Mean ≤15 µg/L TP	Ch. NR 102.06(4)(b)1
		Chlorophyll *a*	Two-story fishery	Mean ≤10 µg/L chlorophyll *a*	WisCALM guidance; Proposed aquatic life criterion in ch. NR 102 revisions
		Aquatic plants – General disturbance (MAC)	Northern Drainage Lake	Tolerant species < 73%	Proposed aquatic life criterion in ch. NR 102 revisions
		Aquatic plants – Phosphorus response (MAC-P)	Northern Drainage Lake	Phosphorus-sensitive species > 51%	Proposed aquatic life phosphorus response indicator in ch. NR 102 revisions
		Oxythermal habitat for two-story fisheries	NA	At least 1 meter of depth with dissolved oxygen >6 and temperatures ≤66 °F	Proposed aquatic life criterion in ch. NR 102 revisions
	Recreation	Total Phosphorus	Two-story fishery	Mean ≤15 µg/L TP	Ch. NR 102.06(4)(b)1
		Frequency of moderate algae levels	Deep (stratified) lake	Chlorophyll *a* does not exceed 20 µg/L for more than 5% of days during summer sampling season	WisCALM guidance; proposed recreation criterion in ch. NR 102 revisions
Musky Bay	Aquatic Life: Warmwater Sport Fish	Total Phosphorus	Shallow (unstratified) Drainage Lake	Mean ≤40 µg/L TP	Ch. NR 102.06(4)(b)3
		Chlorophyll *a*	Shallow (unstratified) lake	Mean ≤27 µg/L chlorophyll *a*	WisCALM guidance; Proposed aquatic life criterion in ch. NR 102 revisions
		Aquatic plants – General disturbance (MAC)	Northern Drainage Lake	Tolerant species < 73%	Proposed aquatic life criterion in ch. NR 102 revisions
		Aquatic plants – Phosphorus response (MAC-P)	Northern Drainage Lake	Phosphorus-sensitive species > 51%	Proposed aquatic life phosphorus response indicator in ch. NR 102 revisions
	Recreation	Total Phosphorus	Shallow (unstratified) Drainage Lake	Mean ≤40 µg/L TP	Ch. NR 102.06(4)(b)3
		Frequency of moderate algae levels	Shallow (unstratified) lake	Chlorophyll *a* does not exceed 20 µg/L for more than 25% of days during summer sampling season	WisCALM guidance; proposed recreation criterion in ch. NR 102 revisions

* Small bays are not assigned separate designated uses from the main lake. For purposes of this analysis data from Stuckey Bay, Chicago Bay, Anchor Bay, Northeast Bay, and Brubaker Bay are reviewed using the same metrics as shown here for the main lake, except that the oxythermal habitat threshold does not apply.
** All surface waters are also assigned wildlife and public health and welfare designated uses, but these are not applicable to this SSC.

4. Evaluation of Data and Analyses Previously Submitted

In 2014, COLA and the Tribe submitted a phosphorus SSC to the department for review and consideration. The analysis, titled "Phosphorus Site-Specific Criteria Proposal for: Lac Courte Oreilles", was developed by LimnoTech in consultation for COLA and the Tribe, and recommended an SSC of 10 µg/L P to be applied to the entire lake using area-weighted averaging (LimnoTech 2014a). Their analysis was updated and resubmitted in 2016 (LimnoTech, 2016).

DNR's analysis builds on much of the work previously done by LimnoTech and other researchers who have studied Lac Courte Oreilles and Musky Bay. Before beginning our analysis, we worked collaboratively with COLA and the Tribe to compile all available data and enter it into the department's central database, the Surface Water Integrated Monitoring System (SWIMS). We also ensured that all historic department-collected data from baseline monitoring and long-term trends monitoring were entered in SWIMS. This created a comprehensive dataset using all known data that could be used for statistical analyses that were not previously feasible. The dataset includes parameters shown in Table 2. Other parameters are also available in SWIMS but were not a focus of this analysis.

Table 2. Parameters and date ranges used for analyses.

Parameter Name	Years With Data - LCO Tribe Data	Years With Data - DNR Data
Chlorophyll *a*	2000-2017	2003-2017
Dissolved Oxygen	1996-1998, 2000-2004, 2007-2017	1975-1979, 1986-1997, 2003-2017
Temperature	1996-1998, 2000-2004, 2007-2017	1975-1979, 1986-1997, 2003-2017
Total Phosphorus	1996, 2000-2017	1988-1997, 2003-2017

Main basins: Cisco and whitefish habitat

- **Dissolved oxygen.** The central position of the LimnoTech report is that low dissolved oxygen levels are causing depletion of habitat for both coldwater fish within the main basins and for musky spawning in Musky Bay. The department's analysis of dissolved oxygen depletion within the main basins is consistent with LimnoTech's findings that hypolimnetic oxygen depletion (HOD) is indeed the primary issue affecting coldwater fish habitat (along with warming trends, also identified by LimnoTech). However, through applying methods more specific to Lac Courte Oreilles, we are able to learn more about the conditions within this lake.
    - LimnoTech's report used a method termed "TDO3" to assess the coldwater habitat in the lake. We applied a variation on the TDO3 method that the department recently developed to assess the "oxythermal habitat" available to coldwater fish in a two-story lake. In the LimnoTech report, a DO of $\geq$6 mg/L was applied to all levels of the water column, which is not suitable for lakes, which naturally experience some hypolimnetic oxygen depletion during the summer. Discussion with COLA, the Tribe, and LimnoTech after receipt of their proposed SSC report actually led to the development of the oxythermal habitat metric, in recognition that the department's existing dissolved oxygen criteria are not appropriate for two-story fishery lakes.
    - We disagree with LimnoTech's assertion that phosphorus is the primary driver of the oxygen depletion that is occurring. The LimnoTech analysis used a published regression relationship

(Chapra and Canale, 1991) between TP and HOD in 26 lakes with widely varying TP concentrations (4 – 120 µg/L) to justify a TP SSC of 10 µg/L. This method assumes that the TP-HOD relationship in Lac Courte Oreilles is similar to the relationship among lakes in Chapra and Canale's dataset. However, the slope of that regression is mainly between groups of low and high TP lakes; there is no relationship between TP and HOD in the low TP (4-12 µg/L) subset of Chapra and Canale's dataset. In addition, the TDO3 and coldwater habitat volume vs TP plots produced by LimnoTech's method show a negligible change in those variables at 10 µg/L relative to current TP concentrations, which calls into question why 10 µg/L was chosen as the proposed SSC.

  - We conducted additional analyses investigating 1) algae levels, 2) the extent of oxygen depletion, 3) the lack of correlation between phosphorus and oxygen depletion, and 4) quantification of sediment oxygen demand. These analyses reveal several plausible alternative causes of DO depletion in Lac Courte Oreilles, and are discussed at length in sections 5.4 through 5.7 in this report.

- **Surface water temperatures.** LimnoTech also identified warming trends that are limiting coldwater habitat in the lake. We ran additional analyses of water temperatures at each of the three main basins for five sections of the depth profiles (see section 5.8). Our results corroborate a warming trend within Lac Courte Oreilles surface waters and epilimnion.

Musky Bay

In Musky Bay, residents are concerned about both aquatic life habitat issues (low dissolved oxygen affecting musky spawning) and recreation issues (inhibition of navigation due to abundance of curly-leaf pondweed and algal mats). These specific concerns, however, are difficult to assess using existing information and methods available to the department. We cannot quantify an impairment or make a clear link between these issues and phosphorus concentrations. While we cannot directly measure or assess the residents' specific concerns with the data and methods available to us, we evaluated whether phosphorus concentrations are having a general impact on aquatic life and recreation by using standard protocols for evaluating chlorophyll *a* concentrations and aquatic plant condition, consistent with the proposed rule. Both metrics indicated healthy conditions and did not warrant a site-specific phosphorus criterion for Musky Bay. However, these conclusions do not preclude future studies that may directly investigate the condition of musky spawning habitat, curly-leaf pondweed and algal mat abundance and establish their relationships to pollutants and nutrients, including phosphorus.

- **Muskellunge spawning.** As stated in the LimnoTech report, both sediment oxygen depletion and suffocation of eggs within loose sediment are likely to be driving the decline in musky spawning success in Musky Bay. The question is whether these are driven by phosphorus or other factors. Musky eggs hatch well before curly-leaf pondweed or algal die-off, so it is unlikely that early season phosphorus inputs are driving oxygen depletion affecting hatching success in the same year. However, accumulation of organic matter over time may drive the oxygen depletion and may also contribute to highly flocculent sediments that may suffocate eggs. We do not have a method to directly assess musky habitat as part of this analysis, but recognize that other collaborative efforts are underway to address this issue.

- **Aquatic plants.** The LimnoTech report discusses impacts of curly-leaf pondweed (CLP), an invasive aquatic plant, on navigational (recreation) use of the bay. Impairment of the recreation use of the bay was recognized by the department when it listed Musky Bay as impaired in 2012 due to the CLP. Treatments for CLP have been ongoing since 2010.

- We re-evaluated the aquatic plant data for Musky Bay to determine whether the overall plant community was healthy and whether the plant community was exhibiting a shift towards phosphorus-tolerant species. This analysis used new assessment procedures that were not available at the time of the LimnoTech report. The aquatic plant metric assesses the overall community composition and whether the species present indicate that disturbance has impacted the community. It showed that the aquatic plant community in Musky Bay always attained the general condition threshold. It did not attain the phosphorus-response threshold in 2011 and 2012, but has attained this threshold in all years since then. This analysis is discussed in section 7.3.
- Currently, the department does not have procedures available for assessing 1) abundance of plants, 2) what constitutes a healthy level of abundance for aquatic life, 3) what level of abundance impairs recreation, and 4) how much phosphorus influences curly-leaf pondweed abundance compared to other factors. While the department recognizes that recreational issues are a major concern for residents, neither of our available indicators of phosphorus impacts, chlorophyll *a* and aquatic plants, indicate a phosphorus impairment. Further evidence of a causal connection would be required to develop a site-specific phosphorus criterion based on aquatic plant abundance.

- **Algal mats.** In conjunction with dense plant growth, periodic algal mats in Musky Bay reportedly impede navigation (recreation). The department's standard assessment methods do not quantify the presence or extent of algal mats. Chlorophyll *a* is measured within the top 2 meters of the water column to quantify the abundance of phytoplankton, and algal mats are specifically avoided. To develop a site-specific phosphorus criterion based on algal mats, two pieces of information are needed: 1) a quantitative measure of algal mat abundance and 2) a demonstrated phosphorus concentration that would limit the extent of algal mats. Neither of these are available at this time.

Musky Bay classification

The LimnoTech report raises the question of whether Musky Bay and/or the other small bays should be given different criteria from the overall lake. The answer to this question has to do with when it is appropriate to assess a bay independently of a main lake. Typically, we do not separately assess different portions of a lake. The lake receives a single criterion and that criterion is assessed only at the deep hole station(s). Although the criterion applies to the lake as a whole, it is not appropriate to measure samples from bays against the lake criterion, since criteria are developed based on the deep part of the lake and are meant to reflect the overall health of the whole lake, with the recognition that it may be natural for shallower portions of the lake to have higher phosphorus and algae levels.

A bay can be assessed separately from the main lake when it is restricted from the main part of the lake and when there is reason to sample the bay separately to determine if impairment is occurring there. In such a case, the bay is assigned the criterion that reflects the characteristics of the bay and the phosphorus and chlorophyll *a* levels expected for that type of system. If the bay has considerably different characteristics from the main lake, then it is assigned a different criterion.

While the LimnoTech report asserts that Musky Bay should be considered a deep (stratified) waterbody, we disagree. Although there is a very small "pothole" with a depth of 19 feet that may stratify occasionally, this does not characterize the rest of the bay. Although there may be low dissolved oxygen levels at the bottom of the bay, that does not lead to the conclusion that the bay is therefore a stratified system. Stratification status is primarily based on temperature profiles; although unstratified lakes are typically well oxygenated, this is not a defining characteristic. Therefore, for purposes of applying a phosphorus criterion to Musky Bay, it is considered an unstratified (shallow) drainage lake. Because it is not stratified and has warm temperatures throughout the water column, it is not suitable habitat for coldwater fish, and is not considered a two-story fishery. Therefore, its aquatic life designated use is Warmwater Sport Fish.

In short, if a bay is to be assessed separately from the overall lake, then the bay must be assigned the most appropriate criterion for the bay. Otherwise, a bay is covered by the whole-lake criterion but is not assessed separately against that criterion. The separate assessment unit for Musky Bay could be removed, in which case it would be covered under the main lake's phosphorus criterion of 15 µg/L, but then we would not assess Musky Bay separately from the main lake. The lake's impairment status would be determined solely from the deep holes of the main basins. Likewise, if other small bays were to be assessed separately, they would likely be assigned shallow drainage lake criteria of 40 µg/L P. However, based on data from the other bays, there is not a need to assess these separately from the whole lake (section 6).

Area-weighted averaging

The LimnoTech analysis proposed using an area-weighted averaging approach for applying the phosphorus criterion to the lake. Employing an area-weighted averaging approach to assessing a lake assumes that we have a strong understanding of the spatial dynamics of nutrients and algae in lakes. This is not the case. Rather, understanding the heterogeneity of basic limnological parameters in space and time is an active area of research. Although the approach is mathematically simple, the appropriate monitoring design to adequately reflect the behavior of the lake is unknown. Limnology has long characterized the pelagic zone of lakes by sampling at the deepest point, and the frequency and number of samples required to give an accurate assessment are well known. Furthermore, an averaging approach gives less ability to diagnose and address particular problem areas if there are localized stressors.

Hydrodynamic modeling

LimnoTech's analysis employed a hydrodynamic model to predict the amount of mixing between Musky Bay and the main basins. We do not disagree that some diffusion from Musky Bay into the West Basin occurs and may mix into the remainder of the lake. However, the assignment of Musky Bay as a separate assessment unit did not rely on an assumption of no mixing.

In addition, we have some concerns with LimnoTech's model. Dye was applied within the lower part of the West Basin, outside of the narrow point defining Musky Bay. It would be more informative to end dye application at the narrowest point. Much of the dye that moved into West Basin is likely to have been from the application within the lower part of the West Basin. This confounds the results to an extent that their interpretation is difficult.

5. MAIN BASINS (WEST, CENTRAL, EAST)

A summary of the attainment status for the three main basins for each of the recreation and aquatic life use metrics contained in the proposed revisions to ch. NR 102 is shown in Table 3. These are described in detail in this section, and root causes of non-attainment of the oxythermal habitat threshold are explored.

Table 3. Summary of attainment status for the three main basins of Lac Courte Oreilles (2012-2018). The metrics in this table are proposed in ch. NR 102 revisions.

Designated Use	Metric (proposed in revisions to ch. NR 102)	Assessment Status
Recreation	Chlorophyll *a* (% summer days with moderate algae levels)	Attains
Aquatic Life	Chlorophyll *a* concentration	Attains
	Macrophytes – General condition	Attains
	Macrophytes – Phosphorus response	Attains
	Oxythermal Habitat – Whitefish	Does not attain
	Oxythermal Habitat – Cisco	Attains (earlier years did not attain)

5.1 Phosphorus

Main findings:

- The total phosphorus (TP) means for all main basins currently attain the applicable criterion of 15 µg/L. Mean TP for the basins are 13.68 µg/L (West Basin), 12.32 µg/L (Center Basin), and 12.10 µg/L (East Basin).
- TP significantly increased in the East Basin since the beginning of our records in 1988. TP has not significantly changed over time in the West Basin or Center Basin, but the period of record is shorter in these basins.

Total phosphorus data were provided by WDNR staff and the Lac Courte Oreilles Tribe. Data collected on Lac Courte Oreilles from 2012-2016 were used in the 2018 assessments. Calculations and data selection methods are outlined in the 2018 Wisconsin Consolidated Assessment and Listing Guidance (WisCALM) document.

In the East Basin and Center Basin the total phosphorus data were clearly below the criteria for both recreation use and aquatic life use. In the West Basin, the upper limit of the two-sided 80% confidence interval was slightly above the criteria, but as per standard protocols in both WisCALM and the proposed rule, this does not result in an impairment listing (Table 4). A waterbody is listed as impaired if the lower confidence limit (i.e. the entire 80% confidence interval) is above the criterion.

Table 4. Total phosphorus (TP) assessment data for West, Center, and East Basins (2018).

				Total Phosphorus (µg/L)		
WBIC	WATERS ID	Station Name	Natural Community	TP Crit. (Rec. & Aqu. Life)	Mean (80% confidence interval)	Rec. & Aqu. Life Status
2390800	15368	West Basin (LCO-2)	TWO-STORY	15	13.68 (11.95-15.64)	May Attain
2390800	15368	Center Basin (LCO-3)	TWO-STORY	15	12.32 (11.03-13.76)	Clearly Attains
2390800	15368	East Basin (LCO-4)	TWO-STORY	15	12.10 (10.77-13.59)	Clearly Attains

To analyze trends over time, we calculated the annual average total phosphorus (TP) concentrations from samples taken at < 2 m deep between June 1 and September 15. Several outlier TP values were removed for the trend analysis. Outliers were identified as > 3 standard deviations from the mean log(TP) for the station or >15 µg/L change in TP in 7 days or less. Outliers were not removed from the assessment calculations in Table 4. TP samples reported as below the detection limit were estimated as $LOD/\sqrt{2}$, which equals 5 µg/L for the TP method. Annual averages were calculated separately for each main basin station. First, daily mean TP was calculated if there were multiple samples on a single day. Then the assessment period was divided into three equal length periods, and the mean TP was calculated for each of these periods. Annual means were calculated from these period means. Years with no samples in one or more periods were excluded from the trend analysis.
Simple linear regressions between TP and year were used to estimate the rate of change in TP over time.

TP significantly increased over time at the Deep Hole site in the East Basin. According to the linear regression, the predicted average TP was 7.2 µg/L in 1988 and 12.0 in 2017 (Figure 3). TP has not significantly changed over time at the deep hole stations in the Central or West Basins (Figure 4). Data first became available in 1996 in the Center and West Basins and in 2000 in Musky Bay, whereas data went back to 1988 in the East Basin. The regression in the East Basin would not be significant without data prior to 1996.

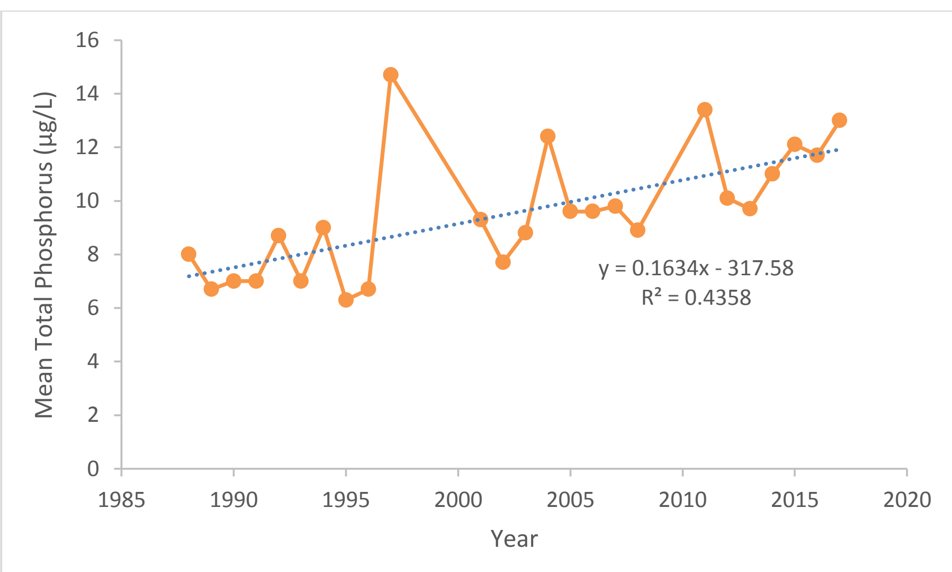

Figure 3. Trend over time of mean annual total phosphorus in the East Basin of Lac Courte Oreilles.

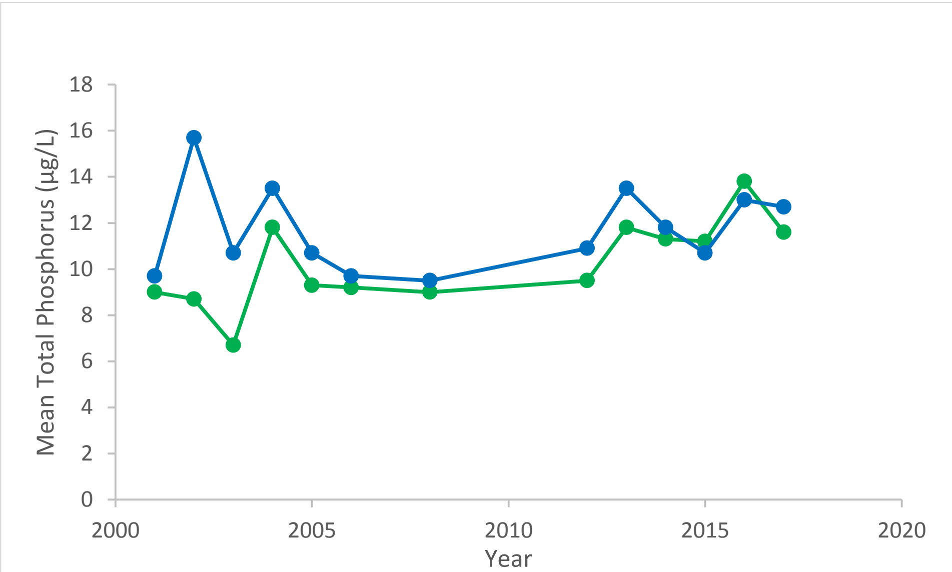

Figure 4. Trends over time of mean annual total phosphorus in the Central (green) and West (blue) Basins.

5.2 Chlorophyll *a*

Main findings:

- All three basins attain the aquatic life chlorophyll *a* threshold for stratified two-story fishery lakes (attained if <10 µg/L). Mean chlorophyll *a* values for the basins are approximately 2 µg/L at each basin.
- All three basins attain the recreation chlorophyll *a* threshold for stratified drainage lakes (attained if <5% of summer days have moderate algae levels). Each basin has zero percent of summer days with moderate algae levels.
- Therefore, TP does not need to be reduced from current concentrations in the main basins to protect for the recreation and aquatic life uses as determined by chlorophyll *a* metrics.
- Chlorophyll *a* has not changed significantly over time in any of the main basins.

Chlorophyll *a* data were provided by WDNR staff and the Lac Courte Oreilles Tribe. Data collected on Lac Courte Oreilles from 2012-2016 were used in the 2018 assessments. Calculations and data selection methods are outlined in the 2018 Wisconsin Consolidated Assessment and Listing Guidance (WisCALM) document.

At all deep-hole stations the chlorophyll *a* data were clearly attained, and far below, the thresholds for both recreation use (Table 5) and aquatic life use (Table 6). The recreation threshold for deep (stratified) drainage lakes is attained if less than 5% of summer days have moderate algae levels, defined as >20 µg/L. Each basin has zero percent of days with moderate algae levels. The aquatic life threshold is a mean concentration of chlorophyll *a* of 10 µg/L; each basin's mean is around 2 µg/L chlorophyll *a*.

Table 5. Main basin recreation use assessment data (2018) for frequency of moderate algae levels. Chlorophyll *a* thresholds in this table are proposed in ch. NR 102 revisions.

				Chlorophyll *a* (*% summer days with moderate algae levels*)		
WBIC	WATERS ID	Station Name	Natural Community	Chl-a Thresh. (Rec.)	Mean (80% confidence interval)	Recreation Status
2390800	15368	West Basin (LCO-2)	TWO-STORY	5%	0 (0-0)	Clearly Attains
2390800	15368	Center Basin (LCO-3)	TWO-STORY	5%	0 (0-0)	Clearly Attains
2390800	15368	East Basin (LCO-4)	TWO-STORY	5%	0 (0-0)	Clearly Attains

Table 6. Main basin aquatic life assessment data (2018) for chlorophyll *a* concentrations. Chlorophyll *a* thresholds in this table are proposed in ch. NR 102 revisions.

				Chlorophyll *a* (µg/L)		
WBIC	WATERS ID	Station Name	Natural Community	Chl-a Thresh. (Aqu. Life)	Mean (80% confidence interval)	Aquatic Life Status
2390800	15368	West Basin (LCO-2)	TWO-STORY	10	2.42 (2.09-2.81)	Clearly Attains
2390800	15368	Center Basin (LCO-3)	TWO-STORY	10	2.12 (1.95-2.31)	Clearly Attains
2390800	15368	East Basin (LCO-4)	TWO-STORY	10	2.14 (1.88-2.44)	Clearly Attains

To analyze trends over time, we calculated annual average chlorophyll *a* concentrations from samples taken at < 2 m deep between July 1 and September 15. Annual averages were calculated separately for each station on the lake. Simple linear regressions were performed predicting chlorophyll *a* based on year for each station. Chlorophyll *a* did not change significantly over time at any of the main basin stations (Figure 5). Low chlorophyll *a* concentrations in Lac Courte Oreilles are not surprising given that phosphorus concentrations are also below 15 µg/L. In most lakes, the increase in chlorophyll *a* per unit increase in TP begins after TP reaches 15-20 µg/L.

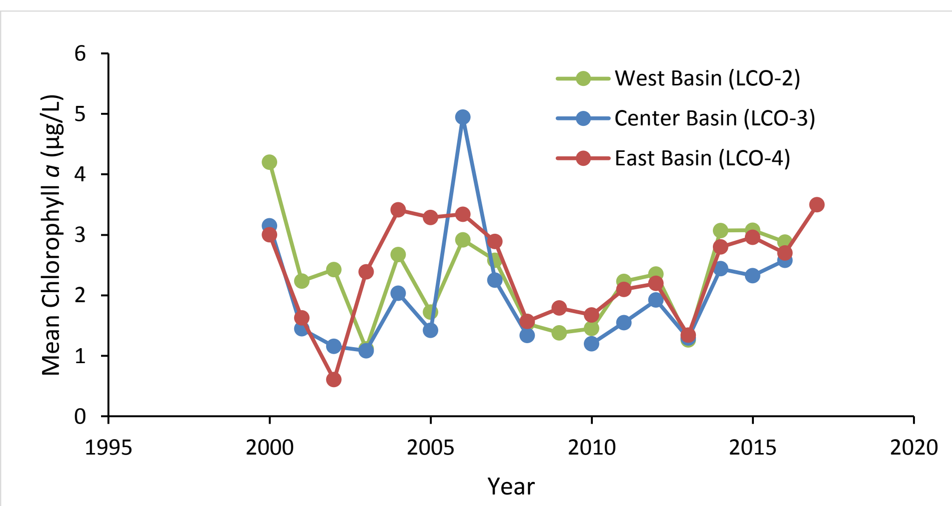

Figure 5. Annual mean chlorophyll *a* over time in the three main basins of Lac Courte Oreilles.

5.3 Aquatic plants

Main findings:
Aquatic plant thresholds for Northern drainage lakes were applied for both the general condition assessment (attained if tolerant species ≤73%) and the phosphorus response assessment (attained if phosphorus-sensitive species are >51%).

- An aquatic plant survey conducted in August, 2010 shows that the whole-lake plant community is healthy. The plant community attains the general condition threshold used to assess for response to a range of disturbances, with tolerant species present at 27% of sampling points. It also attains the threshold that would indicate a response specific to phosphorus, with phosphorus-sensitive species present at 87% of sampling points.
- Therefore, TP does not need to be reduced from current concentrations in the main basins to protect the aquatic plant community.

Aquatic macrophyte data was collected at a grid of sampling points located on the surface of the lake and placed according to baseline recommendations that determine grid resolution according to estimated littoral area and shoreline complexity (Mikulyuk et al., 2010). The grid for Lac Courte Oreilles includes 2254 total sampling points (Figure 6). In August of 2010, the lake was sampled by the Lac Courte Oreilles Conservation Department following the baseline sampling protocol (Hauxwell et al. 2010).

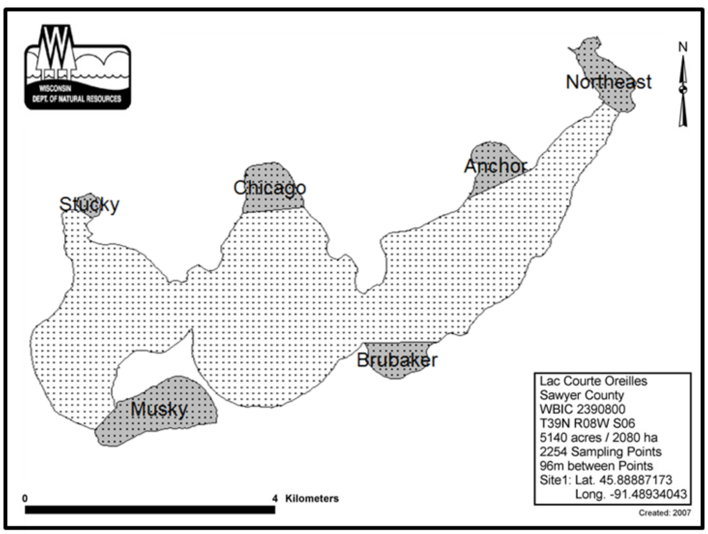

Figure 6. Lac Courte Oreilles aquatic plant sampling grid and bay subsets.

We conducted two different assessments of ecological condition using plant data collected in 2010. The MAC assessment reflects responses linked to a combined set of stressors in the lake, watershed and nearshore area while MAC-P reflects aquatic plant responses related to total phosphorus levels. This bioassessment approach was designed at the whole-lake scale following procedures outlined by Mikulyuk et al. (2017) and is part of the proposed rule package. Both metrics assesses the overall plant community composition and whether the species present indicate that disturbance has impacted the community. The metrics use the abundance of several aquatic plant taxon groups that range in their sensitivity to anthropogenic disturbance to predict the level of disturbance likely experienced by the lake. The assessment is relativistic: lake ecological condition for Lac Courte Oreilles is thereby assessed relative to other northern drainage lakes. We performed MAC and MAC-P assessments at the scale of the entire lake and at several additional bays within the lake (results for Musky Bay and other bays are described in subsequent sections of this report). For all areas sampled, there was no evidence to suggest degradation relative to other northern drainage lakes (Table 7).

Table 7. Draft macrophyte condition assessment decision for the whole lake based on aquatic plant data collected in 2010. The aquatic plant metrics in this table are proposed in ch. NR 102 revisions.

	General Condition Assessment (MAC)			Phosphorus Response Assessment (MAC-P)		
	Threshold (attains if…)	% Tolerant	MAC Status	Threshold (attains if…)	% Phos.-sensitive	MAC-P Status
Lac Courte Oreilles (whole lake)	Tolerant species $\leq$73%	27%	Attains	Phosphorus-sensitive species >51%	87%	Attains

5.4 Two-Story Fishery Habitat

Main findings:

- None of the three basins attains the OLT threshold for whitefish, the more sensitive of the two species. The cisco threshold is attained in all basins over the past five years, but is not attained in the West Basin if earlier years are considered.
- Habitat for whitefish has been marginal since the beginning of our data records (1975), and the OLT has not declined over that period of time. This finding suggests that the whitefish population in Lac Courte Oreilles may be supported by immigration from Whitefish Lake.

A two-story fishery lake is a lake greater than five acres in size that is always stratified in the summer, with the potential for an oxygenated hypolimnion or thermocline (aka metalimnion) which has historic documentation since 1975 of a coldwater fishery (such as cisco, whitefish, or trout).

Cisco, whitefish, and other coldwater fishes need a band of water that has both cold enough temperatures and high enough oxygen for them to survive. At the beginning of the summer, the hypolimnion and thermocline usually have both; but by the end of the summer the dissolved oxygen (DO) is sometimes greatly depleted, squeezing the fish upward into a very narrow layer in the thermocline in which they can survive (Figure 7). During long, hot summers this layer may disappear altogether, causing a fish kill. Therefore, a measure that represents the overall quantity of suitable habitat by combining both DO and temperature is most appropriate for assessing support of the two-story fishery.

WDNR has developed a measure of "oxythermal habitat quantity", which is currently proposed as a new criterion for two-story fishery lakes in revisions to ch. NR 102, Wis. Admin. Code. The proposed criterion requires a layer of water at least 1 meter in depth which attains both a DO of 6 mg/L and the appropriate temperature range for the species expected to be present. The temperature requirement varies by species present. For cisco temperatures within this layer must be below 73°F, for whitefish below 66°F. Because whitefish are the more sensitive species, we apply the temperature limit of 66°F.

To measure a lake's available volume of habitat, vertical temperature and DO profiles are taken in the deep part of the lake while the lake is stratified. For Lac Courte Oreilles, these profiles were assessed from the deep point at each of the three major basins. Multiple profiles are typically needed to account for variability, both during the summer season and across years. The profiles are plotted as temperature vs depth and DO vs depth. The vertical extent of the depth profile at which the DO is 6 mg/L or above and the temperature is at the specified threshold or below (in this case, <66°F) is determined and compared to the threshold. The thickness of the layer of suitable habitat is termed "oxythermal layer thickness", or OLT. Pursuant to the proposed revision to ch. NR 102, Wis. Admin. Code, if the OLT is less than 1 meter at any point during the summer, that year is considered not attaining the threshold; if more than one third of years sampled within the assessment period do not attain the threshold, the lake is considered not attaining the proposed criterion.

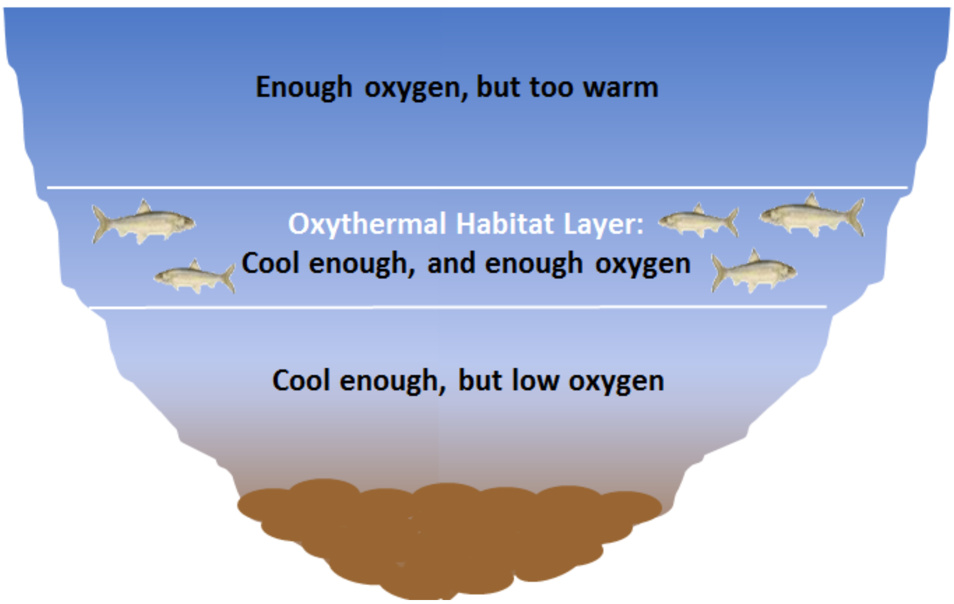

Figure 7. In late summer, cisco and whitefish can live only within the layer of water with high enough oxygen and cold enough temperatures.

Fish kills

According to the WDNR fisheries management files and fish kill database, fish kills have been documented in four separate years for Lac Courte Oreilles; 1966, 2004, 2015, and 2016.

- The 1966 fish kill was a summer kill of mostly perch and believed to be a bacterial infection, most likely columnaris.
- The 2004 fish kill was a winter kill of large crappie and bluegill in Musky Bay due to dissolved oxygen depletion over an extensive shallow area of decomposing plants.
- The 2015 and 2016 fish kills were summer kills of cisco and whitefish in the main basins. The cause of the kills appears to be due to the reduction of oxythermal layer thickness. The cisco and whitefish were forced into the cooler hypolimnion to regulate their body temperatures, however, the hypolimnion was void of oxygen.

Oxythermal Habitat Layer Thickness (OLT)

WDNR has recently developed an assessment methodology that quantifies the amount of available habitat for sensitive coldwater lake fish species (Lyons et al 2017). The methodology, termed Oxythermal Layer Thickness (OLT) identifies bands of suitable habitat along a depth profile where dissolved oxygen and temperature (DO, T) simultaneously meet specific thresholds. The oxythermal layer is the band within which DO is above 6 mg/L and the water temperature is 66°F (18.9°C) or colder for whitefish or 73°F (22.8°C) or colder for cisco. The total depth in which these DO and T thresholds are met is the OLT.

Adequate DO and T profiles samples are available for the each of the three deep hole stations since 1975 for the main deep hole station (East Basin), and since 1998 for the other two stations (West and Central Basins). The proposed OLT assessment deems a two-story fishery lake to be impaired if, within the last 10 years, more than one out of three years has a minimum OLT of less than 1 meter (Table 8). None of the three basins attain this threshold for lake whitefish, but only the West Basin does not attain for cisco. However, if the standard assessment period of the most recent 5 years is applied, OLT is attained for cisco in all three basins.

Table 8. Assessment of oxythermal layer thickness (OLT) pursuant to proposed revisions to NR 102 at the deep hole sampling station for each of the three major basins, East, West, and Central. Each coldwater lake species (18.9 °C for Lake Whitefish and 22.8 °C for Cisco) has a different temperature tolerance, which influences the calculation of OLT. We assessed OLT for two different time windows, using profiles up to the last 5 years or up to the last 10 years.

Station	Species	Number of years		Status: Attains Proposed Criterion?
		total	not attaining	
East	Lake Whitefish	5	5	Does not attain
		10	10	Does not attain
	Cisco	5	1	Attains
		10	2	Attains
West	Lake Whitefish	5	5	Does not attain
		7	7	Does not attain
	Cisco	5	1	Attains
		7	3	Does not attain
Central	Lake Whitefish	5	5	Does not attain
		7	7	Does not attain
	Cisco	5	1	Attains
		7	2	Attains

In a typical year from the beginning to the end of stratification, OLT at all deep hole stations in Lac Courte Oreilles sharply declines, particularly from the beginning of June through mid-July. Because OLT changes throughout the stratification period, it is more appropriate to explore how OLT deviates from the average (i.e. OLT anomalies) to assess whether OLT is changing over the long term. If oxythermal conditions are steadily improving or declining over the long term, we would expect to see a trend, upward or downward, in OLT anomalies over time. Therefore, to assess whether OLT is decreasing in the long-term, we first removed the seasonal trend in OLT. To remove the seasonal trend in OLT, we fitted coefficients to a decay function using non-linear least squares, which predicts OLT with respect to the day of year (Equation 1).

Equation 1.

$$\boldsymbol{OLT} = a\, e^{b*\boldsymbol{DOY}} + c$$

DOY is the integer day of year, and a, b, and c are fitted coefficients. We fit a model for each temperature tolerance for the two sensitive species in Lac Courte Oreilles, Cisco and Lake Whitefish, with tolerances of 22.8 and 18.9 °C, respectively (Table 9). From these models, we computed the residuals (i.e. OLT anomalies), and investigated if there was a trend in the model residuals over time, testing if OLT has significantly changed since the beginning of the record. By regressing OLT anomalies over time, we found that OLT has not been significantly changing over the long term (Figure 9). This indicates that habitat has been marginal for several decades.

Table 9. Coefficients (a, b, and c) and standard error (S) of decay function used to predict the oxythermal layer thickness (OLT) as a function of time between the beginning and end of lake stratification.

	East		West		Central	
	Cisco (22.8 °C)	Lake Whitefish (18.9 °C)	Cisco (22.8 °C)	Lake Whitefish (18.9 °C)	Cisco (22.8 °C)	Lake Whitefish (18.9 °C)
a	131,800	86,630	327,100	886,000	167,400	327,000
b	-0.054	-0.050	-0.0063	-0.067	-0.059	-0.061
c	-5.75	0.74	-4.96	0.61	-5.15	0.40
S	4.44	3.71	3.12	2.44	3.50	2.71

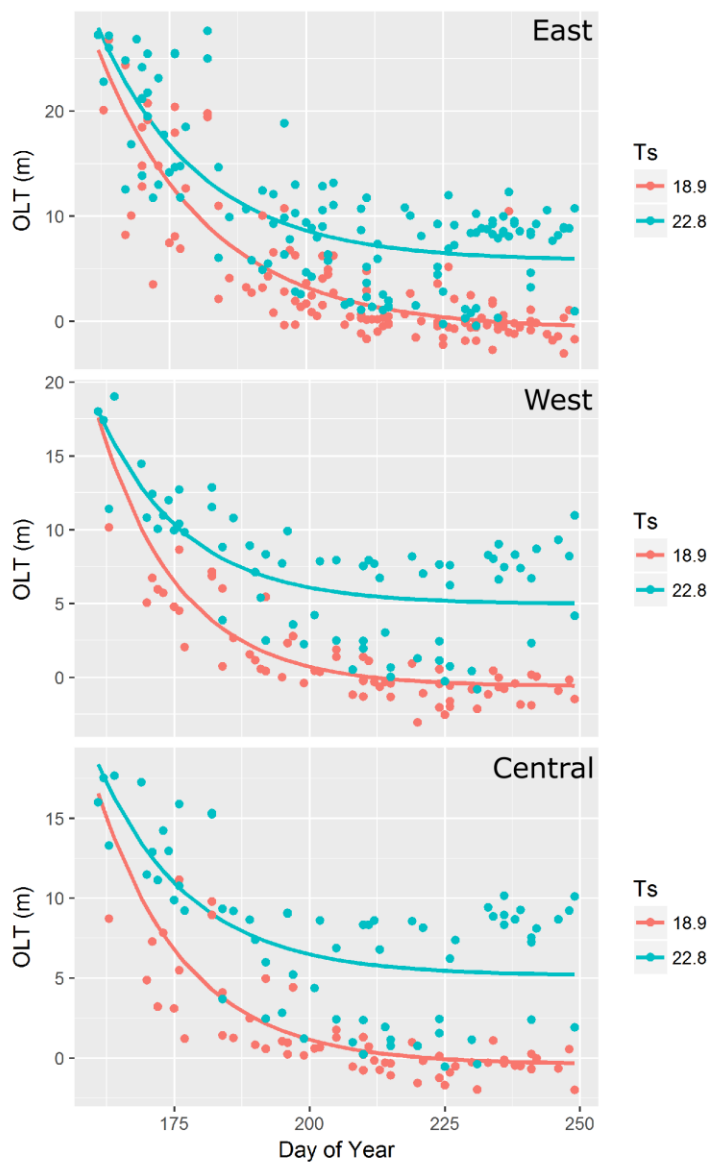

Figure 8. The decline in oxythermal layer habitat (OLT) throughout a given stratification period for two temperature thresholds, Ts = {18.9, 22.8}, corresponding to two sensitive lake species, Cisco and Lake Whitefish, respectively.

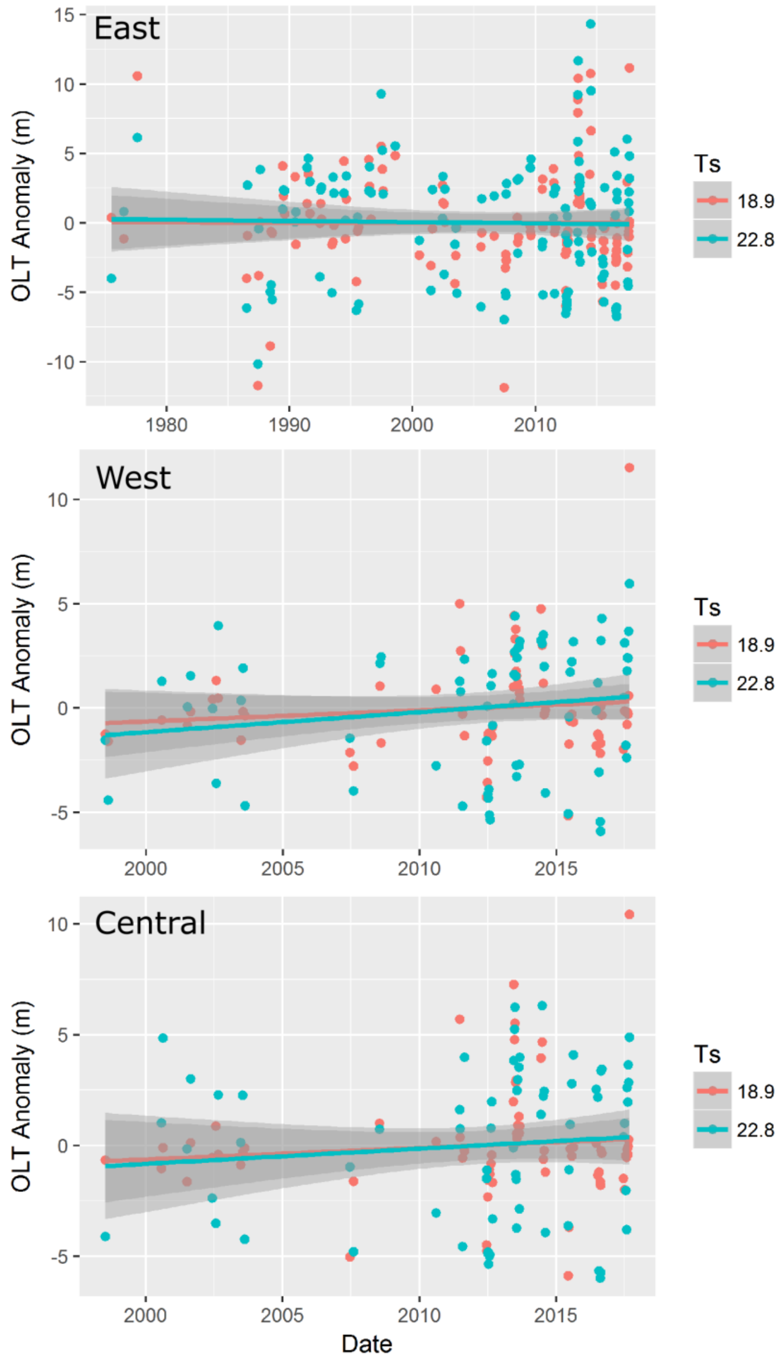

Figure 9. Long-term trends in oxythermal layer thickness (OLT) described as anomalies (deviation from the expected OLT), and calculated as the residuals of the decay model shown in Figure 8. Trends were assessed for two temperature thresholds, Ts = {18.9, 22.8}, corresponding to two sensitive lake species, Cisco and Lake Whitefish, respectively.

5.5 Potential Causes of Two-Story Fishery Impacts

As described in section 5.4, coldwater fish like cisco and whitefish require both cold water and sufficient oxygen to survive. Loss of habitat for coldwater fishes can result from declining oxygen in cold, deep water and from increasing temperatures in epilimnetic water. In Lac Courte Oreilles, Hypolimnetic Oxygen

Demand (HOD) is high and surface waters are warming. Phosphorus can accelerate oxygen depletion by fueling algal growth and bacterial respiration of resulting organic matter. However, decomposition of senesced algae in the water column is not the only process that uses oxygen in a lake and is not the main source of oxygen depletion in Lac Courte Oreilles. A detailed examination of the causes of oxygen depletion in Lac Courte Oreilles found that the relationship between phosphorus and dissolved oxygen is not clear enough to identify a site-specific phosphorus criterion.

There are five processes that could reduce oxythermal habitat: 1) decomposition of organic matter in the water column, 2) aerobic decomposition of organic matter in the sediment that came from internal production (e.g. phytoplankton), 3) aerobic decomposition of organic matter in the sediment that came from external sources (e.g., particulate organic matter washed in from land), 4) oxidation of reduced substances in the sediments (methane, ammonium, nitrite, manganese, iron, sulfide), and 5) warming surface water temperatures (Figure 10). Areal Hypolimnetic Mineralization (AHM) accounts for all four processes that consume oxygen. Hypolimnetic Oxygen Demand (HOD) and Areal Hypolimnetic Oxygen Demand (AHOD) include all aerobic processes that consume oxygen (1 – 3).

Decomposition of organic matter in the water column (1) is directly affected by phosphorus concentrations in most lakes because phosphorus generally limits algal production. If this was the main source of oxygen depletion, reducing phosphorus concentrations in Lac Courte Oreilles may be advised. Decomposition of sediment organic matter derived from algae (2) can be linked to phosphorus, but may not immediately respond to reduced in-lake phosphorus concentrations because the pool of sediment organic matter may take decades to deplete (Matthews & Effler 2006). The final three pathways are unrelated to in-lake phosphorus concentrations.

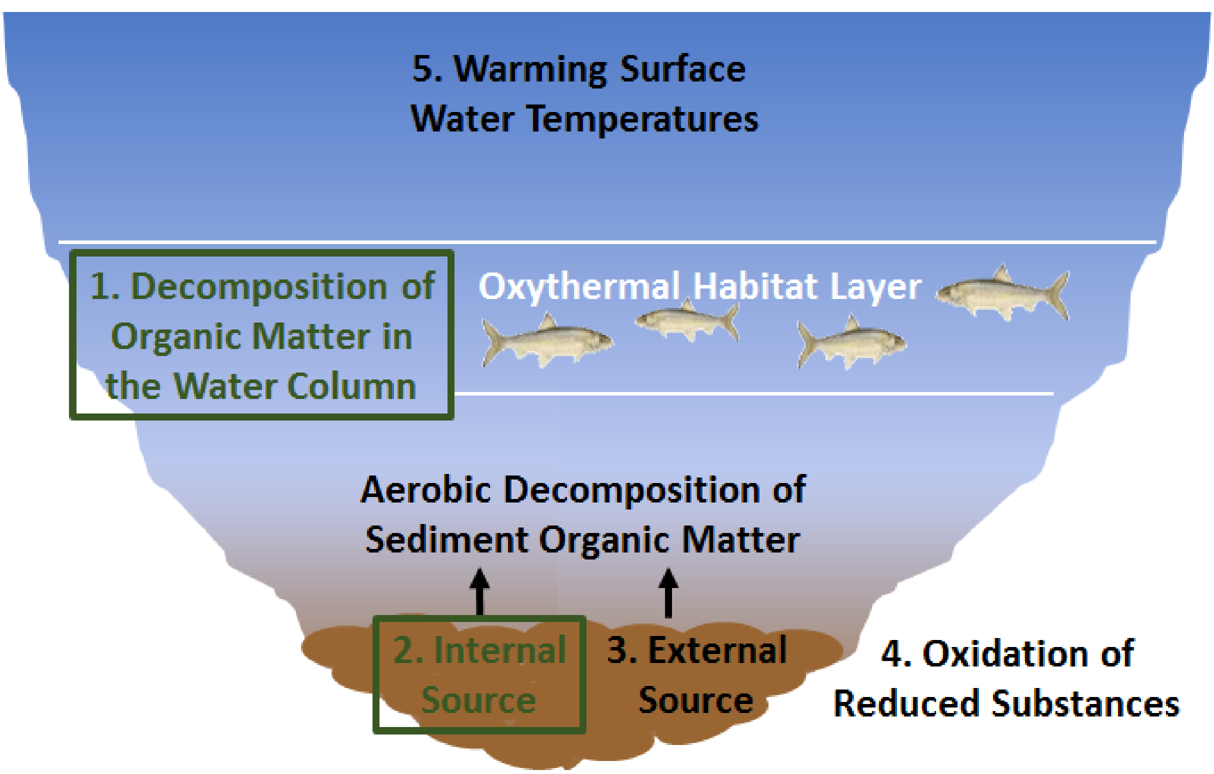

Figure 10. Diagram illustrating the processes that could reduce oxythermal habitat for coldwater fish. The processes boxed in green could be affected by phosphorus concentrations, but those listed in black occur independent of phosphorus.

We evaluated five potential causes of negative impacts to coldwater fish habitat and their relationship to phosphorus. Our findings are briefly summarized here and described in detail in the following sections.

1) Decomposition of organic matter in the water column

- This is a small component of total Hypolimnetic Oxygen Demand (HOD) in Lac Courte Oreilles.
    - Concentrations of chlorophyll *a* in the water column are low.
    - Tests of oxygen demand from sediment cores from Lac Courte Oreilles indicate that more than half of total HOD comes from aerobic decomposition of organic matter in the sediment. This means that less than half of HOD comes from decomposing organic matter in the water column.
- Reducing phosphorus concentrations is unlikely to reduce HOD.
    - The relationship between phosphorus concentrations and HOD was non-existent in the West and Central Basins and was variable in the East Basin.
    - In the East basin, phosphorus has increased over time, but HOD has not.
    - In the West basin, one measure of HOD increased over time, but phosphorus has not.
    - HOD has been high enough to eliminate the oxythermal layer even in years with phosphorus concentrations as low as 7 µg/L.
    - In the LimnoTech analysis, a model developed by Chapra and Canale (1991) was used to propose an SSC of 10 µg/L. However, this model is not an appropriate method for determining a site-specific phosphorus criterion for Lac Courte Oreilles. A relationship observed across lakes as in the Chapra and Canale study will not necessarily hold true within a single lake. In Lac Courte Oreilles, HOD is higher for a given phosphorus level than in other lakes and does not show a similar decline in HOD with declining phosphorus.

2&3) Aerobic decomposition of sediment organic matter

- This is a large component of HOD.
    - A laboratory study of sediment cores, though not an exact measure of in-lake dynamics, estimates that this accounts for 59% of HOD in the East Basin, 92% in the Central Basin, and 75% in the West Basin.
    - Previous studies report high organic matter content in the sediments.
- The influence of phosphorus on accumulation of sediment organic matter is uncertain.
    - Further studies are needed to determine the current sedimentation rate and whether the organic matter mostly comes from within the lake or from land.
        - If future studies determine the organic matter mostly comes from algal production in the lake, then reducing phosphorus concentrations would reduce the influence of organic matter decomposition on HOD over time.
        - If sediment organic matter mostly comes from land, management options for reducing external inputs should be examined. Reducing phosphorus would not be effective.

4) Oxidation of reduced substances in the sediment

- A portion of HOD is caused by the oxidation of reduced substances, such as methane, ammonium, nitrite, manganese, iron, or sulfide. Further study is needed to quantify how much these processes contribute to oxygen reduction.
- Given Lac Courte Oreilles's hypolimnetic thickness (z) of 7.8 m and a comparison to other lakes, reduced substances could account for 50-75% of Areal Hypolimnetic Mineralization (AHM). This means that oxygen consumption is likely even higher than estimated using HOD (oxygen consumption = HOD plus oxidation of reduced substances).

- Limited data found high concentrations of iron in the hypolimnion of the West Basin with an increase over the summer season, providing evidence that oxidation of at least one reduced substance is occurring in Lac Courte Oreilles.
- Reducing phosphorus will not affect oxidation of reduced substances.

5) Warming surface water temperatures

- Historically, the epilimnion was often cold enough to provide suitable habitat for coldwater fish even in late summer, but since 1975 epilimnetic and surface water temperatures have increased by 2.5 and 2.7ºC, respectively.
- If the warming trends continue, future warming will further exacerbate thermal stress for cisco and whitefish.
- Reducing phosphorus will not reduce water temperature.

5.6 Aerobic Decomposition of Organic Matter

Understanding Hypolimnetic Oxygen Demand (HOD)

Oxygen consumption can be divided into three phases throughout the course of the summer (Gelda et al. 1995; Figure 11). These phases are determined by whether the hypolimnion has oxygen or not. Period 1 is from the onset of stratification to the date that anoxia first occurs at the sediment-water interface. Oxygen is consumed via algal respiration and aerobic respiration by bacteria as organic matter is decomposed. Period 2 occurs from the onset of anoxia in the hypolimnion to complete anoxia in the hypolimnion. Reduced substances begin to diffuse out of the sediment and into the water column. Period 3 is defined by complete anoxia in the hypolimnion. Reduced substances from the anoxic sediment accumulate in the hypolimnion at this time with some loss to the epilimnion.

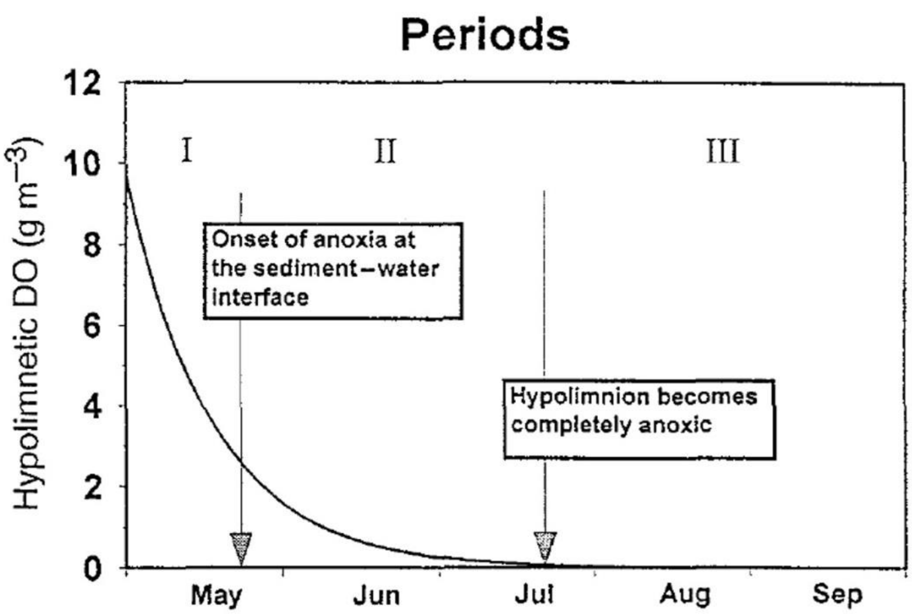

Figure 11. Figure borrowed from Gelda et al. (2012) showing the three periods of oxygen status in the hypolimnion and sediments. Reduced substance reactions occur under anoxic conditions.

In lakes, oxygen is depleted in two main ways: 1) organic matter is broken down through aerobic respiration and 2) under anaerobic conditions, reduced substances diffuse from deep layers of the sediment up to the sediment surface. The combination of both sources of oxygen demand is called Areal Hypolimnetic Mineralization (AHM). The Hypolimetic Oxygen Demand (HOD) and the Areal Hypolimnetic Oxygen Demand (AHOD) are both measures of aerobic respiration. HOD is a volumetric estimate whereas AHOD is an areal estimate of the oxygen demand in the hypolimnion. Because reduced substances oxidation can begin to occur before the hypolimnion is completely anoxic, it is partially included in the estimates of HOD and AHOD. Natural elements in the sediment—methane, ammonium, nitrite, manganese, iron, and sulfide—use oxygen as they change form. These reduced substances reactions that use oxygen can be expressed with a series of chemical equations (from Muller et al. 2012):

$$CH_4 + 2O_2 \rightleftarrows CO_2 + 2H_2O \qquad (1a)$$

$$NH_4^+ + 2O_2 \rightleftarrows NO_3^- + H_2O + 2H^+ \qquad (1b)$$

$$NO_2^- + 0.5O_2 \rightleftarrows NO_3^- \qquad (1c)$$

$$Mn(II) + 0.5O_2 + 2H^+ \rightleftarrows Mn(IV) + H_2O \qquad (1d)$$

$$Fe(II) + 0.25O_2 + H^+ \rightleftarrows Fe(III) + 0.5H_2O \qquad (1e)$$

Hypolimnetic Oxygen Demand: Estimated Values, Temporal Trends and Phosphorus Relationship

Main findings:

- AHOD is high in the East Basin given its hypolimnetic thickness, and average in the Central and West Basins.
- AHOD does not increase over time in the East and Central Basins. There is some evidence for increasing AHOD over time in the West Basin, but it is not corroborated with both measures of AHOD.
- There was no relationship between TP and AHOD in the West and Central basins. The relationship in the East Basin was highly variable, with high AHOD values along the entire TP gradient.
- Given the lack of a strong relationship between TP and AHOD in Lac Courte Oreilles, the model from Chapra and Canale (1991) used in the LimnoTech analysis is inappropriate for setting a site-specific phosphorus criterion.

Methods

We began by visually examining all temperature and dissolved oxygen profiles (Figure 12) for the entire record in which those data have been recorded for Lac Courte Oreilles (starting in 1975) to 1) determine if there were enough profiles (2 or more) within any given year to calculate AHOD, and 2) assess whether samples were taken during lake stratification (if samples were taken when the lake was well-mixed, they were discarded).

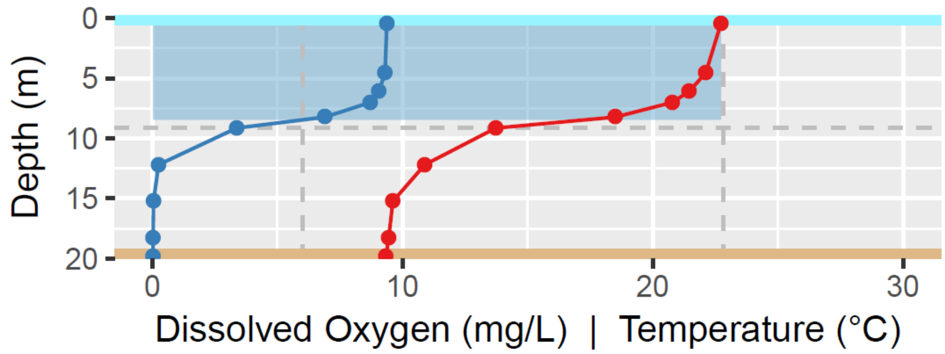

Figure 12. An example of temperature and dissolved oxygen plotted as profiles along the water column for the Lac Courte Oreilles deep hole station, taken on August 22nd, 2013.

We then visually examined the consumption of oxygen within the summer for each year by plotting DO over the day of year (Figure 13). We excluded profiles after the day of year in which the lake bottom became anoxic.

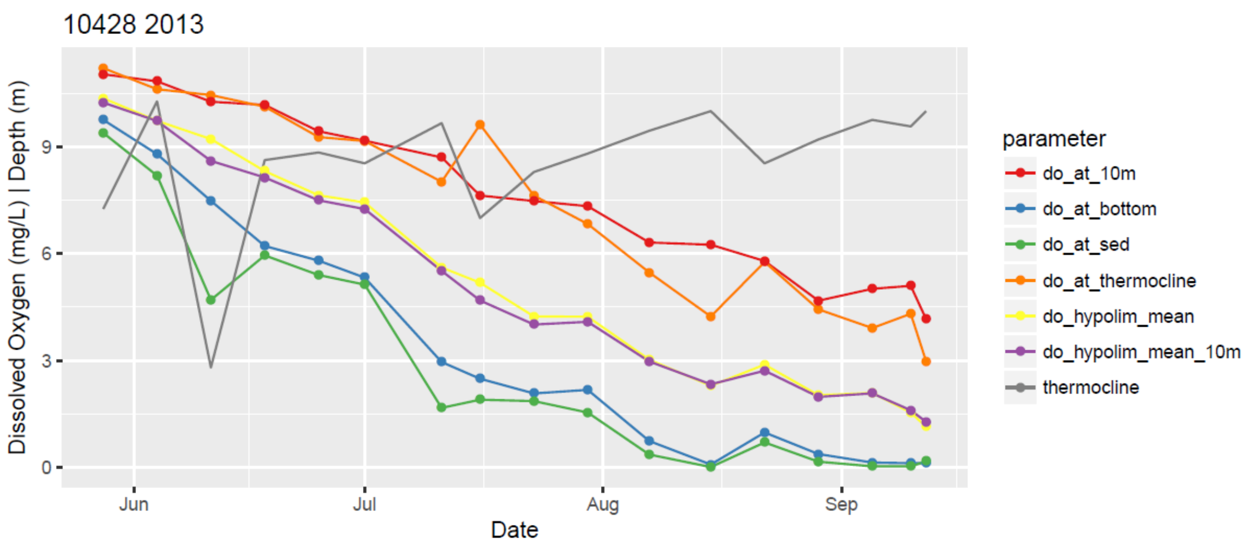

Figure 13. Example plot of the consumption of dissolved oxygen throughout the summer of the year 2013 for the East Basin deep hole station in Lac Courte Oreilles The depth of the thermocline is also plotted using the same y-axis except in units of meters. The DO metrics are DO at 1) 10m (do_at_10m), 2) 1.5 meters from the bottom (do_at_bottom), 3) at the sediment interface (do_at_sed), 4) at the thermocline, 5) the mean across the hypolimnion using a derived thermocline, and 6) the mean across the hypolimnion using 10m as the thermocline.

Once the DO profiles had been screened for quality samples, we calculated the mean hypolimnetic DO for each profile in each year in which at least 2 profiles were taken. The mean hypolimnetic DO was calculated using two different hypolimnion designations: 1) assuming the thermocline was 10m below the surface, and 2) using a variable thermocline depth which was calculated as the depth where the temperature profile had the largest percent change. The first approach assumes a constant thermocline depth over time, which is not always the precise depth, but is generally true and screens out oxygen concentrations in the bottom of the metalimnion. The second approach accounts for variation of thermocline depth on different dates, but sometimes inaccurately portrayed the temperature profile and included part of the metalimnion. Because the analytical approach slightly impacted the results, both results are presented in this report. We think that AHOD calculated assuming the top of the hypolimnion at 10 m depth is the most robust measure of AHOD.

To calculate AHOD, we began by fitting a regression line using the equation:

Equation 2.

$$\boldsymbol{DO}_Y = \beta_{0,Y} + \beta_{1,Y} * \boldsymbol{DOY_Y} + \varepsilon$$

where Y is the year in which the regression was fitted, DOY_Y is the day of year, $\beta_{0,Y}$ is the intercept coefficient, $\beta_{1,Y}$ is the slope coefficient, and ε is the error term. The slope of the regression line, $\beta_{1,Y}$ is equivalent to the volumetric HOD in units of mg/L/day.

To compare Lac Courte Oreilles' HOD values to the literature, we converted the volumetric HOD to AHOD by multiplying HOD by mean hypolimnetic depth (z_h). We calculated z_h for each of the three distinct basins using the following equation:

Equation 3.

$$z_h = {}^{V_h}/_{SA_h}$$

where V_h is the volume of the hypolimnion and SA_h is the surface area of the top of the hypolimnion, both derived from bathymetric maps in a GIS. The above methodology resulted in 22, 11, and 11 AHOD values (East, West, and Central, respectively), one for each year, ranging between the years 1986 and 2017 (Table 10).

Estimated HOD and AHOD

AHOD was higher in the East Basin than in the Central and West Basins. The mean (95% confidence intervals) AHOD was 0.87 $g/m^2/d$ (0.80 – 0.95) in the East Basin, 0.39 $g/m^2/d$ (0.35 – 0.43) in the Central Basin, and 0.48 $g/m^2/d$ (0.41 – 0.54) in the West Basin. This is not surprising given the greater hypolimnetic depth in the East Basin (7.8 m vs. 3.2 in the Center Basin and 3.7 m in the West Basin).

The mean hypolimnion depth is a good predictor of the Areal Hypolimnetic Mineralization rate in eutrophic French and Swiss Lakes (Figure 14, from Muller et al. 2012). We cannot estimate AHM for Lac Courte Oreilles because we do not know how much oxygen is being used by reduced substances oxidation. The Areal Hypolimnetic Oxygen Demand is one component of AHM and is thus likely underestimates total AHM on its own. In the East Basin of Lac Courte Oreilles, AHOD is higher than expected given the mean hypolimnion depth of the East Basin (Figure 14). Not accounting for reduced substances' oxidation, AHOD is approximately what one would expect given z_H in the Central and West Basins.

Table 10. Areal hypolimnetic oxygen demand (AHOD) values for two models: 1) using a derived thermocline (t), and 2) using a thermocline assumed to be at a depth of 10m. Also reported are r^2 values for each model for each year (values of "—" are reported if only two DO profiles were available in each year. Annual TP mean calculation methods are described in section 5.1.

Station	Year	n	TP	HOD_t	$AHOD_t$	r^2_t	HOD_{10}	$AHOD_{10}$	r^2_{10}
East	1987	3		0.14	1.06	0.97	0.13	1.01	0.99
	1988	3	8.0	0.09	0.69	0.96	0.08	0.64	0.97
	1989	3	6.7	0.09	0.71	0.99	0.09	0.69	0.95
	1990	3	7.0	0.13	1.01	0.99	0.12	0.97	0.99
	1991	3	7.0	0.09	0.70	0.99	0.08	0.64	0.99
	1992	2	8.7	0.10	0.78	—	0.10	0.80	—
	1993	3	7.0	0.12	0.95	0.99	0.11	0.83	0.99
	1994	2	9.0	0.12	0.91	—	0.11	0.89	—
	1995	2	6.3	0.13	1.00	—	0.09	0.71	—
	1996	3	6.7	0.10	0.74	1.00	0.09	0.74	0.99
	1997	2	14.7	0.14	1.12	—	0.15	1.14	—
	2001	3	9.3	0.10	0.80	0.98	0.10	0.79	0.96
	2002	2	7.7	0.15	1.15	—	0.15	1.14	—
	2003	3	8.8	0.11	0.90	1.00	0.12	0.92	1.00
	2007	2	9.8	0.07	0.53	—	0.10	0.79	—
	2011	4	13.4	0.11	0.87	0.99	0.10	0.76	1.00
	2012	9	10.1	0.11	0.88	0.99	0.11	0.88	0.99
	2013	17	9.7	0.09	0.67	0.95	0.08	0.65	0.96
	2014	7	11.0	0.11	0.83	0.99	0.10	0.82	0.99
	2015	6	12.1	0.13	1.04	0.98	0.15	1.14	0.99
	2016	6	11.7	0.13	1.04	1.00	0.13	1.01	1.00
	2017	4	13.0	0.17	1.31	1.00	0.16	1.27	1.00
West	1998	2		0.07	0.25	—	0.09	0.35	—
	2001	2	9.7	0.14	0.51	—	0.11	0.39	—
	2002	2	15.7	0.13	0.48	—	0.14	0.51	—
	2003	3	10.7	0.12	0.44	0.98	0.12	0.44	1.00
	2011	2		0.14	0.51	—	0.07	0.28	—
	2012	5	10.9	0.16	0.61	0.98	0.14	0.53	0.98
	2013	7	13.5	0.13	0.49	0.93	0.14	0.53	0.99
	2014	4	11.8	0.17	0.63	0.99	0.15	0.55	0.98
	2015	5	10.7	0.15	0.56	0.96	0.18	0.67	1.00
	2016	4	13.0	0.15	0.54	1.00	0.13	0.50	1.00
	2017	3	12.7	0.21	0.77	0.96	0.13	0.48	1.00
Central	1998	2		0.07	0.21	—	0.09	0.30	—
	2001	2	9.0	0.16	0.53	—	0.13	0.40	—
	2002	3	8.7	0.11	0.34	1.00	0.10	0.33	0.94
	2003	3	6.7	0.12	0.38	0.92	0.13	0.40	1.00
	2011	3		0.10	0.32	1.00	0.09	0.30	0.97
	2012	7	9.5	0.12	0.40	0.99	0.12	0.38	0.98
	2013	12	11.8	0.11	0.35	0.98	0.11	0.34	0.99
	2014	5	11.3	0.14	0.45	1.00	0.13	0.43	0.98
	2015	7	11.2	0.15	0.48	0.94	0.16	0.50	0.99
	2016	5	13.8	0.14	0.44	1.00	0.13	0.43	1.00
	2017	4	11.6	0.17	0.54	0.99	0.15	0.48	0.99

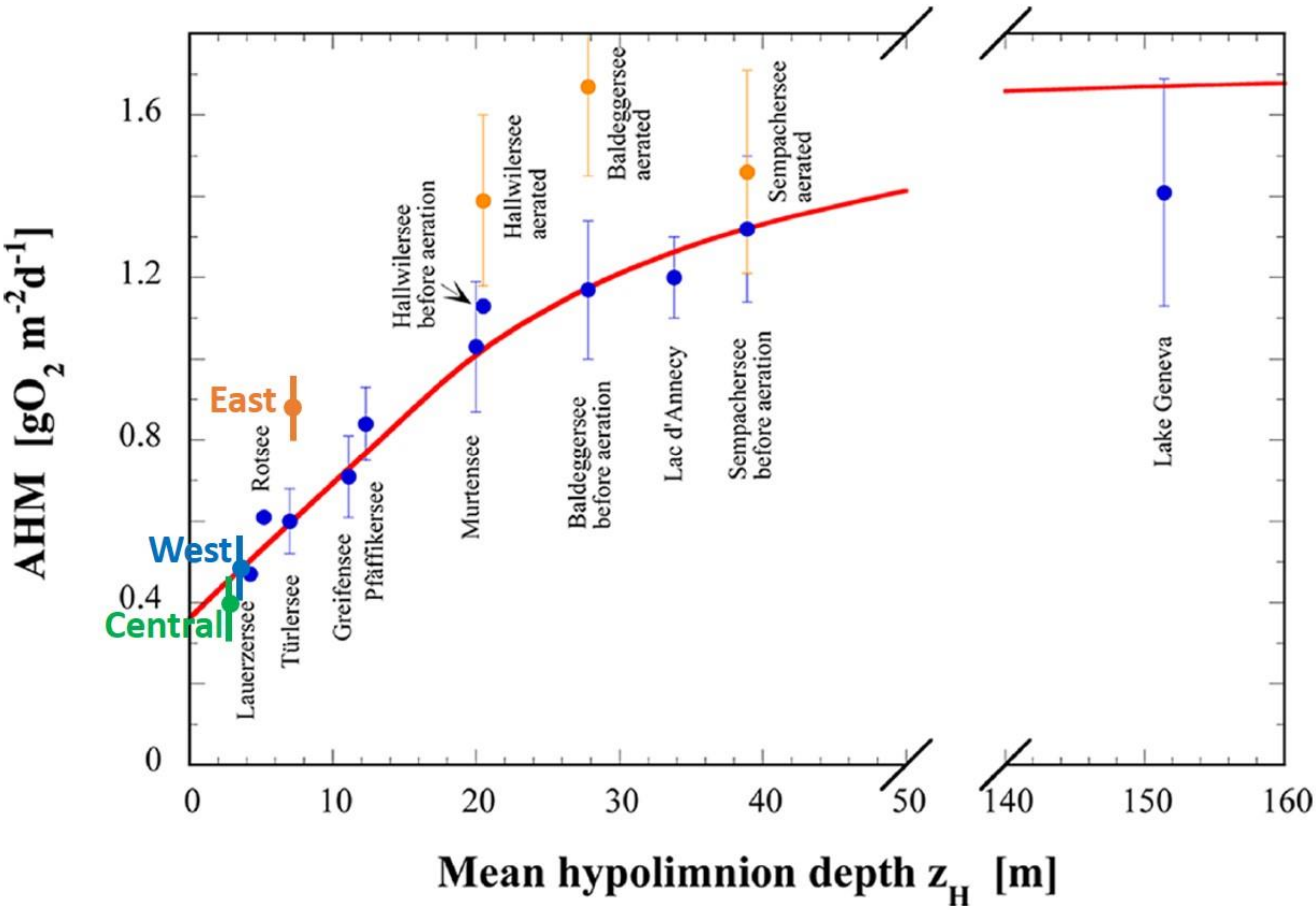

Figure 14. Mean and 95% confidence intervals of the Areal Hypolimnetic Oxygen Demand (AHOD) of the East, Central, and West Basins in Lac Courte Oreilles compared to the Areal Hypolimnetic Mineralization (AHM) rates of 10 eutrophic lakes and Lake Geneva plotted against the average hypolimnion thickness, z_H (Figure 1 in Muller et al. 2012). AHOD is only one component of AHM, so is likely an underestimate of AHM in Lac Courte Oreilles.

Temporal Trends and Relationship with Phosphorus

Given the perceived worsening problem of oxythermal habitat for coldwater fish, we expected AHOD to increase over time. We particularly expected to see an increase in AHOD over time in the East Basin commensurate with the increase in TP. The only case where AHOD significantly increased was in the West Basin when the thermocline was defined at the depth of greatest change in temperature ($AHOD_t$ in Table 11, Figure 15), but 1) the significance of this trend was not corroborated when the thermocline was defined at a fixed depth of 10 meters, and 2) the sample size is not large enough (n=11) to rule out a spurious correlation. Therefore, based on the available data, there is not sufficient evidence for an increasing trend in AHOD over time for any of the three deep hole stations.

If oxythermal habitat is dependent on in-lake TP concentrations, we must establish the degree of dependency to set an SSC for in-lake TP concentrations. We hypothesized that AHOD would be correlated with TP. The only case where AHOD significantly correlated with TP was in the East basin when the thermocline was defined at a fixed depth of 10 meters ($AHOD_{10}$ in Table 11), but the significance of this trend was not corroborated when the thermocline was defined at the depth of greatest change in temperature. The main argument against using this relationship to derive a site-specific phosphorus criterion in the East Basin is the high degree of variation in AHOD given TP (Figure 16). The regression only explained 22% of the variation. AHOD can be as high at 7.5 µg/L TP as at 15 µg/L TP. The lack of a clear relationship between TP and

AHOD, and the fact that AHOD was high enough to deplete hypolimnetic oxygen even during years with TP well below 10 µg/L mean that a TP concentration that would support the two-story fishery cannot be identified from this historical data.

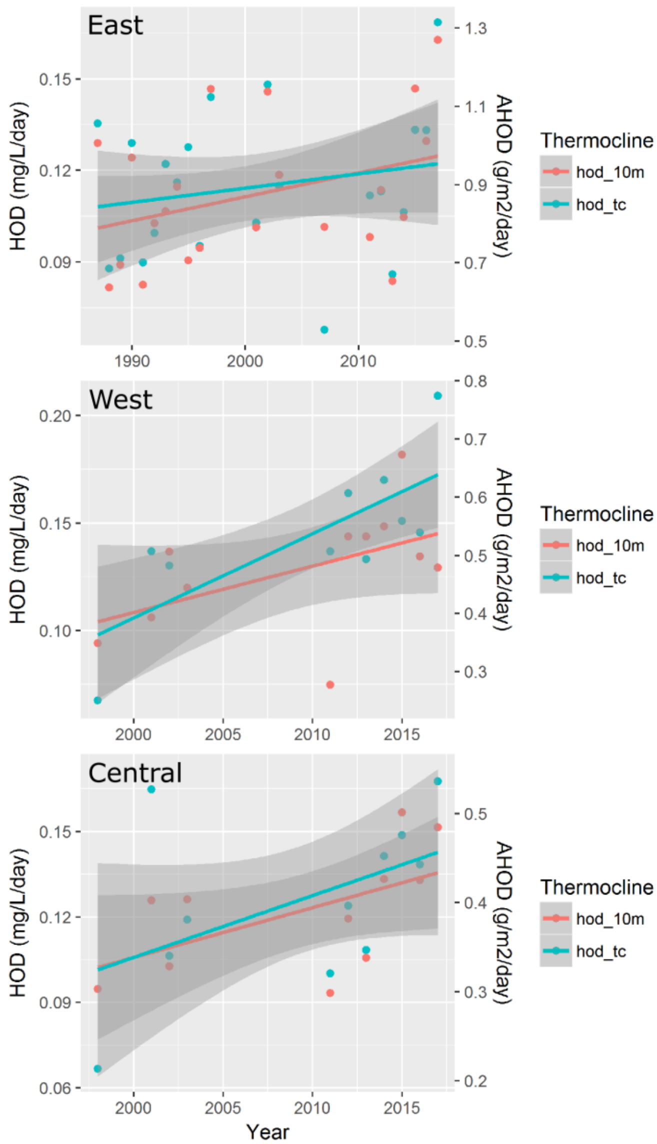

Figure 15. Trends in volumetric hypolimnetic oxygen demand (HOD), also expressed as areal HODs (AHOD), which is the HOD multiplied by the mean hypolimnetic depth (7.8, 3.7, and 3.2 for the East, West, and Central basins, respectively). HOD was calculated in two ways: 1) assuming the thermocline was 10m below the surface (hod_10m), and 2) using a variable thermocline depth which was calculated as the depth where the temperature profile had the largest percent change (hod_tc).

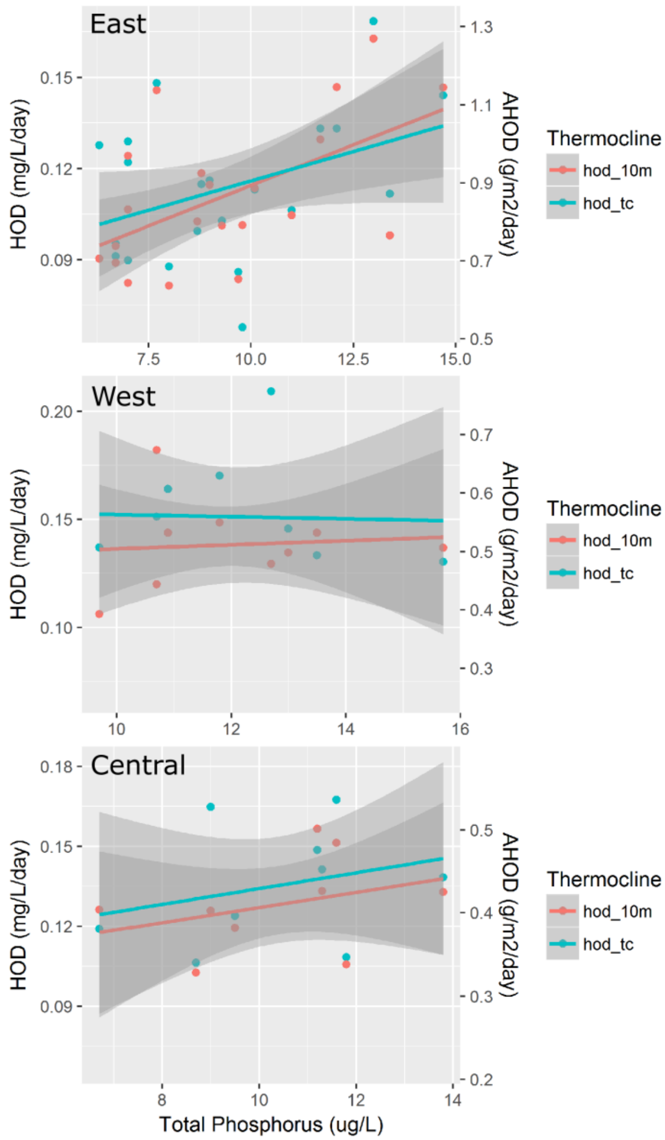

Figure 16. Correlation between volumetric hypolimnetic oxygen demand (HOD) and total phosphorus [HOD also expressed as areal HODs (AHOD), which is the HOD multiplied by the mean hypolimnetic depth]. HOD was calculated in two ways: 1) assuming the thermocline was 10m below the surface (hod_10m), and 2) using a variable thermocline depth which was calculated as the depth where the temperature profile had the largest percent change (hod_tc).

Table 11. We explored several hypotheses for determining change in areal hypolimnetic oxygen demand (AHOD). For each of the three deep hole stations (i.e. East, West, and Central), we tested if AHOD had changed over time (Y = year), and if it correlated with changes in total phosphorus (TP). For each of these AHOD trend analyses, we tested two methods for calculating AHOD: by assuming a fixed thermocline depth of 10 meters ($AHOD_{10}$), and by defining the thermocline as the depth at which the greatest change in temperature is observed ($AHOD_t$). For each AHOD trend, reported here are the slope coefficients (β_1) of each linear regression, the p-value of the slope coefficient, and the coefficient of determination (r^2). For the time trend, β_1 can be interpreted as the change in g/m^2/day for each year, and for the TP relationship, β_1 can be interpreted as the change in g/m^2/day for a 1 µg/L increase in TP concentration.

Station	Trend	n	β_1	p	r^2
East	$AHOD_t = f(Y)$	22	0.0036	0.369	< 0.01
	$AHOD_{10} = f(Y)$		0.0061	0.111	0.08
	$AHOD_t = f(TP)$	21	0.0301	0.080	0.11
	$AHOD_{10} = f(TP)$		0.0415	**0.009**	0.27
West	$AHOD_t = f(Y)$	11	0.0145	**0.005**	0.55
	$AHOD_{10} = f(Y)$		0.0080	0.109	0.18
	$AHOD_t = f(TP)$	9	-0.0018	0.932	< 0.01
	$AHOD_{10} = f(TP)$		0.0035	0.834	< 0.01
Central	$AHOD_t = f(Y)$	11	0.0069	0.121	0.16
	$AHOD_{10} = f(Y)$		0.0056	0.072	0.24
	$AHOD_t = f(TP)$	9	0.0095	0.470	< 0.01
	$AHOD_{10} = f(TP)$		0.0091	0.384	< 0.01

Comparison to Limnotech's Approach for Developing a Site-Specific Phosphorus Criterion
Limnotech (2016) assigned a site-specific TP criterion for Lac Courte Oreilles using a power law relationship derived from a multi-lake study that showed hypolimnetic oxygen demand varies as a function of TP (Chapra and Canale, 1991):

Equation 4.

$$AHOD = 0.086 * TP^{0.478}$$

where AHOD is the areal hypolimnetic oxygen demand in units of g/m^2/day and TP is the in-lake phosphorus concentration. The power law relationship was fit across 26 lakes ranging from phosphorus concentrations between 1 and 100 µg/L.

There are several reasons why it is inappropriate to apply this model equation to Lac Courte Oreilles. The primary reason is that the authors note that the model equation should only be used for lakes where algae comprised the largest percentage of oxygen demand, which is not the case here (section 5.6). Further, the combination of a low sample size, large range of phosphorus concentrations, and large error term in the regression ultimately rendered this method unsuitable for predicting the narrow range of AHOD response to TP reductions in Lac Courte Oreilles. TP concentrations in Lac Courte Oreilles over the full period of record were low with little variability ($\mu = 9.8$ µg/L and $\sigma = 2.9$ µg/L for the East Basin; $\mu = 11.7$ µg/L and $\sigma = 2.2$ µg/L for the West Basin; $\mu = 10.3$ µg/L and $\sigma = 2.5$ µg/L for the central basin). Compared to the lakes in the Chapra paper, Lac Court Oreilles covers a small range of phosphorus values. When we examine lake-specific Lac Courte Oreilles data, AHOD values at a given phosphorus concentration are all higher than predicted by the Chapra model (Equation 4, Figure 17).

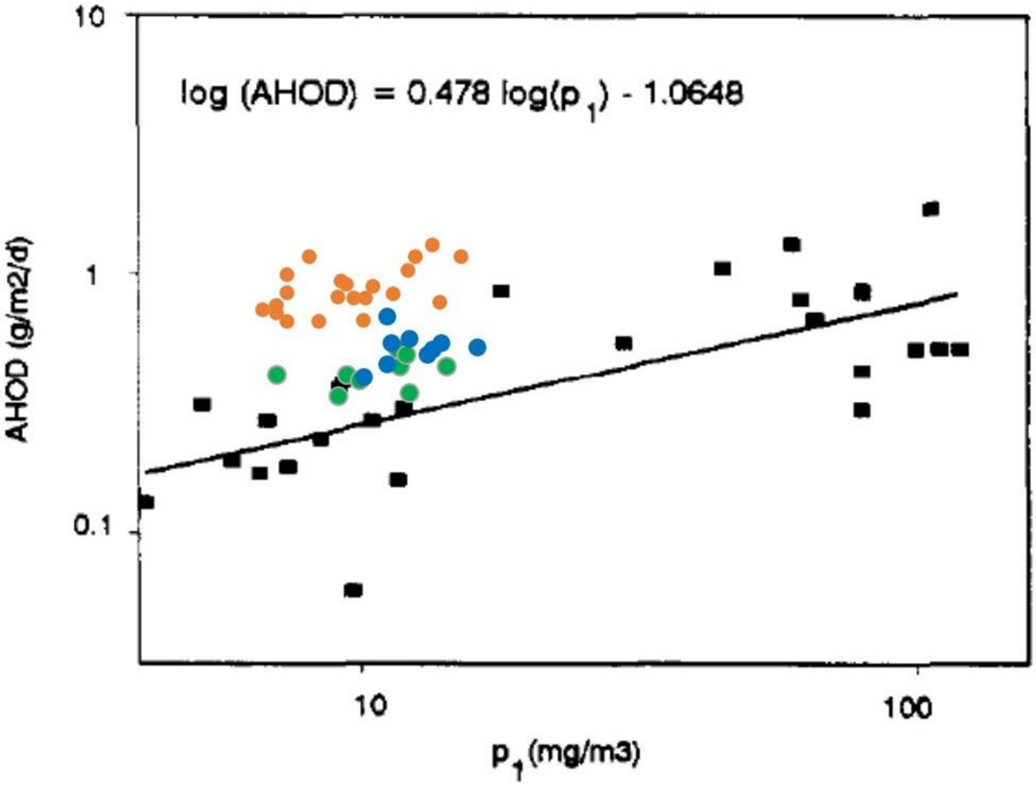

Figure 17. Relationship between lake phosphorus concentration and Areal Hypolimnetic Oxygen Demand in a wide variety of lakes as compared to Lac Courte Oreilles. Annual estimates from the East Basin (orange), Central Basin (green), and West Basin (blue) of Lac Courte Oreilles are graphed on top of figure 3 in Chapra and Canale 1991.

Furthermore, the Chapra model should only be applied to waterbodies whose hypolimnetic oxygen demand is controlled by planktonic algal biological oxygen demand. The following section (5.6) shows that this assumption is not met in Lac Courte Oreilles. In fact, more than half of oxygen consumption comes from sediment oxygen demand. Comparison to the literature also suggests that reduced substances contribute to a large portion of the oxygen demand in Lac Courte Oreilles. Thus, the Chapra model should not be used to set phosphorus targets for Lac Courte Oreilles.

5.7 Aerobic Decomposition of Sediment Organic Matter

Main findings:

- Aerobic decomposition of sediment organic matter is a large component of HOD. A laboratory study of sediment cores, though not an exact measure of in-lake dynamics, estimates that this accounts for 59% of HOD in the East Basin, 92% in the Central Basin, and 75% in the West Basin.
- Previous studies report high organic matter content in the sediments.

Sediment Organic Matter Content and Internal Phosphorus Loading

The sediment in Lac Courte Oreilles has high organic matter content (23-52%), high moisture content, and low bulk density (James 2012). Sediment cores were taken in the 3 deep basins of Lac Courte Oreilles and in

Musky Bay and Stuckey Bay. The sediments in the deep basins also have very high iron content with over 50% of total phosphorus in the sediments bound to iron. Approximately 18-27% of biologically-labile phosphorus was bound to iron in Musky and Stuckey Bays. Internal nutrient loading of phosphorus was high throughout the lake (anoxic fluxes from the sediments were 3.01 to 5.10 mg/m^2 d at 12ºC in the deep West, Central, and East basins and was 2.96 mg/m^2 d at 25ºC in Musky Bay).

Sediment Oxygen Demand – Laboratory Study

Sediment oxygen demand (SOD) was assessed with sediment cores from the three main basins. This analysis estimates the aerobic component of the decomposition of sediment organic matter. Sediment cores were collected on January 25, 2018 by WDNR staff. SOD tests were performed by William James at the University of Wisconsin – Stout using the following methods.

Undisturbed replicate (three per basin) sediment cores were collected at the deep hole stations in each of the main lake basins. A gravity sediment coring device (Aquatic Research Instruments, Hope ID) equipped with an acrylic core liner (6.5-cm ID and 50-cm length) was used to collect sediment. The core liners, containing both sediment and overlying water, were immediately sealed using rubber stoppers and stored in a covered container until analysis. Additional lake water was collected for incubation with the collected sediment.

In the laboratory, the upper 2 cm of the sediment core was transferred intact to a small aluminum dish and placed on a trivet inside a 1 liter glass beaker (10 cm diameter by 20 cm height). The trivet positioned the sediment core 3 cm above a micro-magnetic stir bar that was located in the bottom of the beaker to provide circulation during SOD experiments. Very small magnetic stir bars (10 mm length by 3 mm diameter) were used to create gentle circulation in each system. The beaker containing a sediment dish, trivet, and magnetic stir bar was slowly filled with ~0.75 L of filtered (Gelman A/E glass fiber; nominal pore size = 2 µm) lake water that had been pre-equilibrated with atmospheric oxygen. The SOD systems were placed on a magnetic stir motor an environmental chamber. Temperature was maintained at 12-13°C throughout the incubation period.

A YSI Model 6600 data sonde, fitted with a temperature and dissolved oxygen (DO) probe, was inserted into the beaker so that no airspace was left in the system and secured in the environmental chamber with a stand and clamp. The DO probe was positioned 5 cm above the sediment interface for SOD determinations. Prior to the experiment, DO probes were pre-calibrated against known Winkler titrations. Temperature and DO were monitored at 5 minute intervals in the sediment system for a periods of 2-3 days. Data sonde DO calibration was checked after each experiment.

The rate of DO depletion was calculated as the change in DO mass over the linear range of depletion, divided by time and the area of the sediment dish (mg/m^2/d). Because the starting DO varied from 8.5 to 12 mg/L among the incubations, and the depletion was approximately linear below 8 mg/L DO in all incubations, a period starting at 8 mg/L DO and running for 48 hours was used to calculate the rate of DO depletion for all incubations. A control system that did not contain sediment was also monitored in order to account for any DO demand in the water column. SOD was calculated as the rate of DO depletion in the sediment system minus the water oxygen demand (WOD) estimated from the control system. Then, because the incubation temperatures (12-13°C) were warmer than the average summer lake bottom temperature (10°C), SOD_{10} was estimated from a modified Arrhenius expression (Chapra 1997).

$$SOD_{10} = \frac{SOD_T}{\theta^{T-10}}$$

SOD_{10} and SOD_T are values of AHOD at temperatures of 10°C and T°C, respectively, and θ is the temperature coefficient. A value of 1.0718 was used for the temperature coefficient θ (Q_{10} = 2; e.g., Burns 1995).

SOD_{10} varied from 0.30 to 0.55 g/m^2/day in the individual incubations. The mean SOD_{10} for the three replicates in each basin were 0.51 g/m^2/day in the East basin and 0.36 g/m^2/day in both the Central and West basins. Given the mean AHOD estimates for each basin, this corresponds to SOD accounting for 59%, 92%, and 75% of the AHOD in the East, Central, and West Basins, respectively.

Core	SOD (mg/L/min)	WOD (mg/L/min)	Temperature (C)	SOD (g/m^2/day)	SOD_{10} (g/m^2/day)
East 1	0.000949	0.000111	12.24	0.52	0.45
East 2	0.001106	0.000111	11.83	0.62	0.55
East 3	0.001102	0.000111	12.10	0.62	0.53
Central 1	0.000683	0.000085	12.60	0.37	0.31
Central 2	0.000750	0.000085	12.16	0.41	0.36
Central 3	0.000864	0.000085	12.48	0.49	0.41
West 1	0.000597	0.000022	12.66	0.36	0.30
West 2	0.000782	0.000022	11.98	0.47	0.41
West 3	0.000745	0.000022	12.44	0.45	0.38

Future Study

A wide variety of techniques may be used for better characterizing lake sediments and for identifying their source (Meyers and Ishiwatari 1993). Examples include: organic matter C/N ratios, C and N stable isotopes, humic substances, and lipid biomarkers. In addition, sediment traps can quantify gross sedimentation and burial rates, which would help identify the relative importance of contemporary sedimentation.

5.8 Oxidation of Reduced Substances in the Sediment

Main Findings:

- A portion of HOD is caused by the oxidation of reduced substances, such as methane, ammonium, nitrite, manganese, iron, or sulfide. Further study is needed to quantify how much these processes contribute to oxygen reduction.
- Given Lac Courte Oreilles's hypolimnetic thickness (z) of 7.8 m and a comparison to other lakes, reduced substances could account for 50-75% of Areal Hypolimnetic Mineralization (AHM). This means that oxygen consumption is likely even higher than estimated using AHOD (oxygen consumption = HOD plus oxidation of reduced substances).
- All three basins have high iron levels in the sediment. Additionally, limited data found high concentrations of iron in the hypolimnion of the West Basin with an increase over the summer season (up to 8 mg/L), providing evidence that oxidation of at least one reduced substance is occurring in Lac Courte Oreilles. The other two basins had much lower iron concentrations in the hypolimnion.
- Reducing phosphorus will not affect oxidation of reduced substances.

In addition to aerobic decomposition, oxidation of reduced substances (methane, ammonium, nitrite, manganese, iron, sulfide) is a source of oxygen consumption. Lac Courte Oreilles does not have sufficient data to estimate reduced substances' oxidation. By comparing the inverse of hypolimnetic thickness (z_H) in

Lac Courte Oreilles to other lakes in the world, we estimate that the contribution of reduced substances to total AHM could be 50-75% (Figure 18).

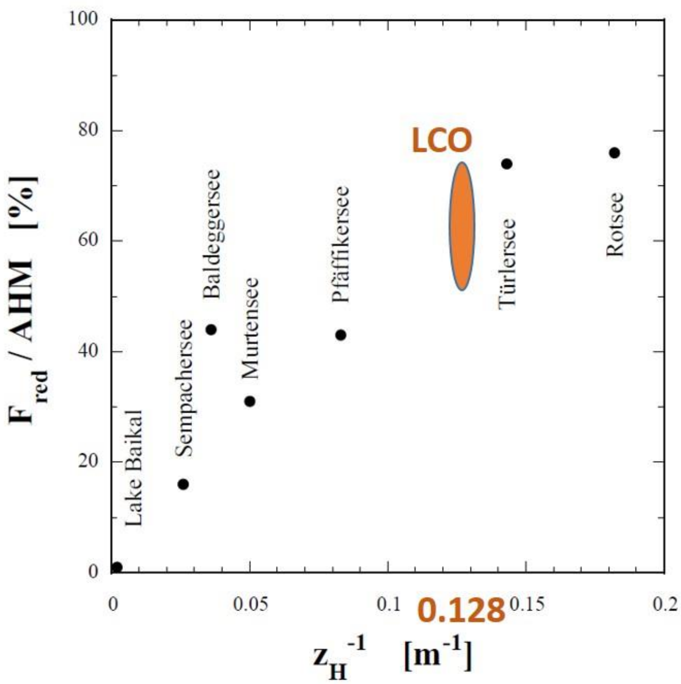

Figure 18. The contribution of reduced substances (Fred) to the total Areal Hypolimnetic Mineralization (AHM) rate depends on the ratio of sediment area to the total volume of the hypolimnion (zH). This figure shows the expected range of Lac Courte Oreilles (LCO based on its z_H. (Figure S1-2 in Muller et al. 2012).

Further study is needed to quantify the contribution of reduced substances' oxidation to the total AHM. There are sporadic samples of some reduced substances in the hypolimnion of Lac Courte Oreilles, but not enough to determine whether the concentration of reduced substances increases over time after the hypolimnion becomes anoxic. There was sufficient iron data from the hypolimnion in 2013 to examine the accumulation of iron over time. In the West Basin, (LCO-2), iron concentrations increased at the end of summer after a month or two of anoxia, which begins in June/July. Iron remained low in the Central (LCO-3) and East (LCO-4) Basins (Figure 19). This indicates that iron could be contributing to oxygen depletion in the West Basin. If large amounts of readily oxidizable ferrous iron and sulfide in surficial sediments are available, HOD may be higher than expected given TP.

Future investigations should help quantify the importance of reduced substance oxidation. The concentration of reduced substances in the hypolimnion should be monitored over time in all three basins, particularly after anoxia develops in the hypolimnion (e.g., as in Gelda et al. 1995). Pore-water profiles of reduced substances along sediment profiles can also be measured to determine fluxes of reduced substances out of the sediment (e.g., as in Matzinger et al. 2010).

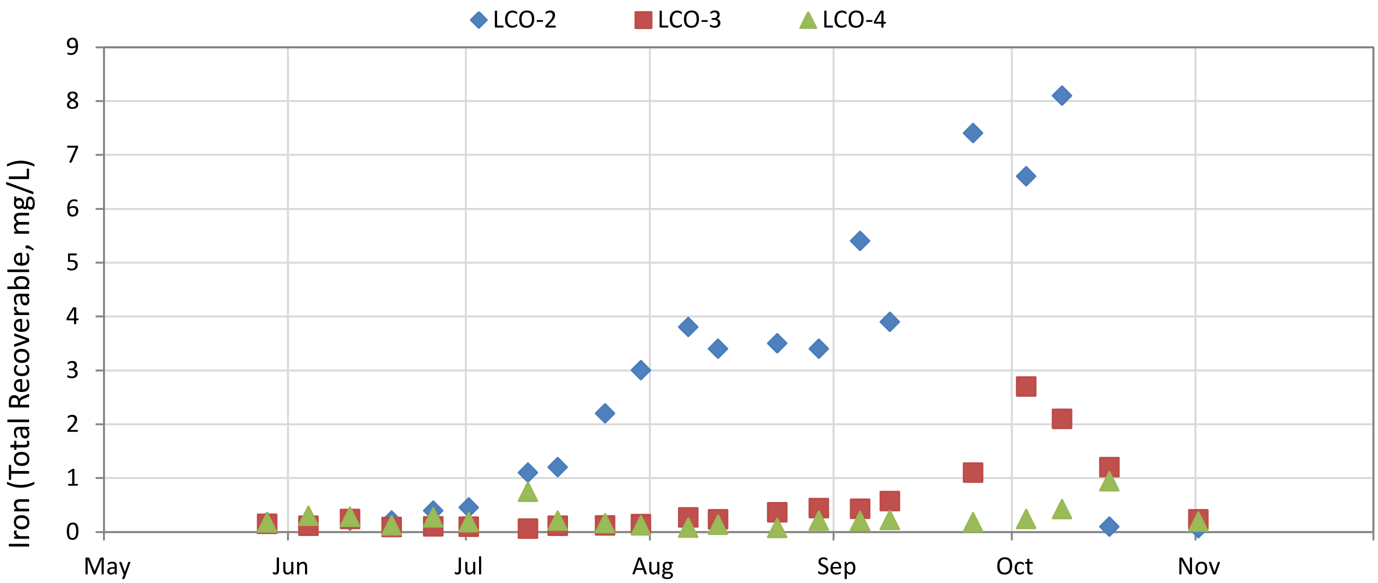

Figure 19. Hypolimnetic iron concentrations over the course of the summer in 2013 in the West (LCO-2), Central (LCO-3), and East (LCO-4) Basins of Lac Courte Oreilles.

5.9 Surface Water Temperature Trends

Main findings:

- Historically, a large portion of the OLT occurred in the epilimnion. The epilimnion was often cold enough to provide suitable habitat for coldwater fish even in late summer, but since 1975 epilimnetic and surface water temperatures have increased by 1.7 and 2.15°C, respectively. There is no long-term trend in water temperature in the lower layers of the lake (thermocline, hypolimnion, or bottom).
- If the warming trends continue, future warming will further exacerbate thermal stress for cisco and whitefish.
- Reducing phosphorus will not reduce water temperature.

Observed Temperature Trends

Habitat suitability for sensitive fishes in Lac Courte Oreilles is most strongly dependent on DO and temperature. We can investigate habitat suitability directly by calculating the OLT, but investigating OLT does not illustrate independently which metric, temperature or DO, could be the cause of low OLT. Although we generally did not find significant trends in OLT (Figure 9) or HOD over time (Table 11), we investigated if warming temperatures may have been a stressor for cisco or lake whitefish.

Because temperature varies seasonally, we used the same methodology for investigating long-term trends in temperature that was used to investigate long-term trends in OLT. We took out the seasonal trend in temperature by first modeling temperature as a function of day of year, and second regressing the residuals of the seasonal model over time. Temperature varies seasonally in a different way than OLT (sinusoidally rather than exponentially), so a different function was used for de-trending (Figure 20). We used non-linear least squares to fit coefficients of a sinusoidal function.

Equation 5.

$$\boldsymbol{T_d} = a + b\sin(2\pi c * \boldsymbol{DOY})$$

where T_d is the temperature for a given depth d, DOY is the integer day of year, and a, b, and c are fitted coefficients (Table 12). Temperatures were predicted independently for five sections of the depth profile: 1) 1.5 meters from the bottom, 2) the mean of temperatures across the hypolimnion defined as 1.5 meters below the thermocline and 1.5 meters above the bottom, 3) the thermocline defined as the bottom depth of the interval in which the temperature per unit depth changed the most, 4) the mean of temperatures across the epilimnion defined as the surface temperature to 1.5 meters above the thermocline, and finally 5) the surface temperature. Once the coefficients were fit for each of the five profile sections, we calculated residuals, which we refer to as temperature anomalies.

Temperature trends analyses showed a warming of surface and epilimnetic temperatures at the eastern deep hole station, and cooling of hypolimnetic temperatures at the western and central deep hole stations (Figure 21 and Table 12). Epilimnetic and surface temperatures at the eastern deep hole station increased on average 0.04 and 0.05°C per year, respectively (1.7 and 2.15°C total since 1975). Given the level of significance of this trend combined with the large sample size, it is likely that warming temperatures were a stressor for Cisco and Lake Whitefish, particularly because historically suitable habitat is often found in the epilimnion in Lac Courte Oreilles even during warm summer months. At the other two deep hole stations, temperature profiles were only sampled since 1998. Since 1998, marginally significant cooling trends were observed in the hypolimnion. This trend is strongly influenced by residually cooler temperatures from two successive cold winters between 2013 and 2014. Because this trend is influenced by weather rather than longer term climatic shifts, and the cooling trend only occurs below the thermocline where DO tends to be below the threshold of suitability (at least 6 mg/L), the cooling trend likely had no effect on the availability of suitable oxythermal habitat.

Table 12. Coefficients and performance metrics for two temperature models at multiple depth profile sections. The seasonal models are sinusoidal models that describe temperature as a function of the day of year. The sinusoidal seasonal models each have three coefficients, a, b, and c, and the model's performance can be assessed by the standard error S. The long-term trend models assess whether temperature anomalies (residuals of the seasonal model) have changed over time. The long-term trend model is a standard linear regression with slope β_1 in units of degrees C per year. The fits of each linear regression can be assessed using the p-value of the slope term, p, and the r^2.

		Seasonal Model				Long-Term Trend		
Station	**Depth profile**	a	b	c	S	β_1	p	r^2
East	Surface	13.42	-10.54	0.0035	1.95	0.05	**< .01**	0.08
	Epilimnetic Mean	12.55	-9.80	0.0035	2.40	0.04	**< .01**	0.06
	Thermocline	10.31	-6.19	0.0035	2.65	0.03	**0.05**	0.02
	Hypolimnetic Mean	8.42	-2.48	0.0033	1.48	0.02	0.12	0.01
	Bottom	7.97	-1.92	0.0031	1.34	0.01	0.15	0.01
West	Surface	14.55	-9.48	0.0035	1.60	-0.03	0.33	< .01
	Epilimnetic Mean	13.68	-8.90	0.0035	1.46	-0.03	0.32	< .01
	Thermocline	11.53	-5.94	0.0034	2.09	-0.02	0.63	< .01
	Hypolimnetic Mean	9.83	-3.07	0.0033	1.59	-0.05	**0.04**	0.04
	Bottom	9.51	-2.20	0.0002	1.48	-0.06	**0.01**	0.06
Central	Surface	14.25	-9.89	0.0035	1.61	-0.03	0.32	< .01
	Epilimnetic Mean	13.54	-9.19	0.0035	1.47	-0.05	0.09	0.02
	Thermocline	11.39	-5.93	0.0033	2.57	-0.11	**0.03**	0.04
	Hypolimnetic Mean	9.56	-3.07	0.0033	2.15	-0.07	**0.03**	0.04
	Bottom	9.17	-2.46	0.0032	1.93	-0.08	**0.01**	0.06

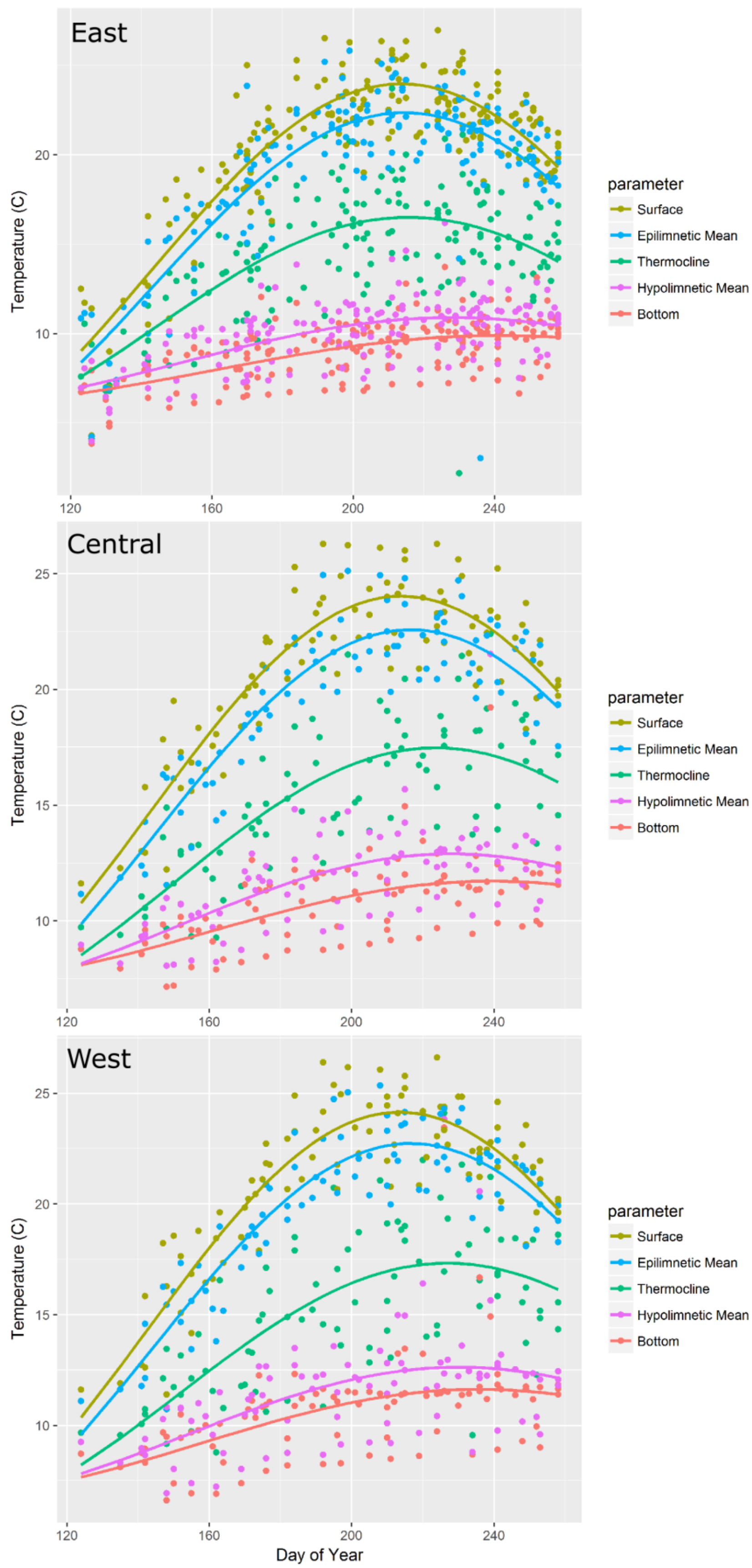

Figure 20. The rise and fall of lake temperatures during the stratification period of Lac Courte Oreilles for several depth profiles, each fit with a sinusoidal model.

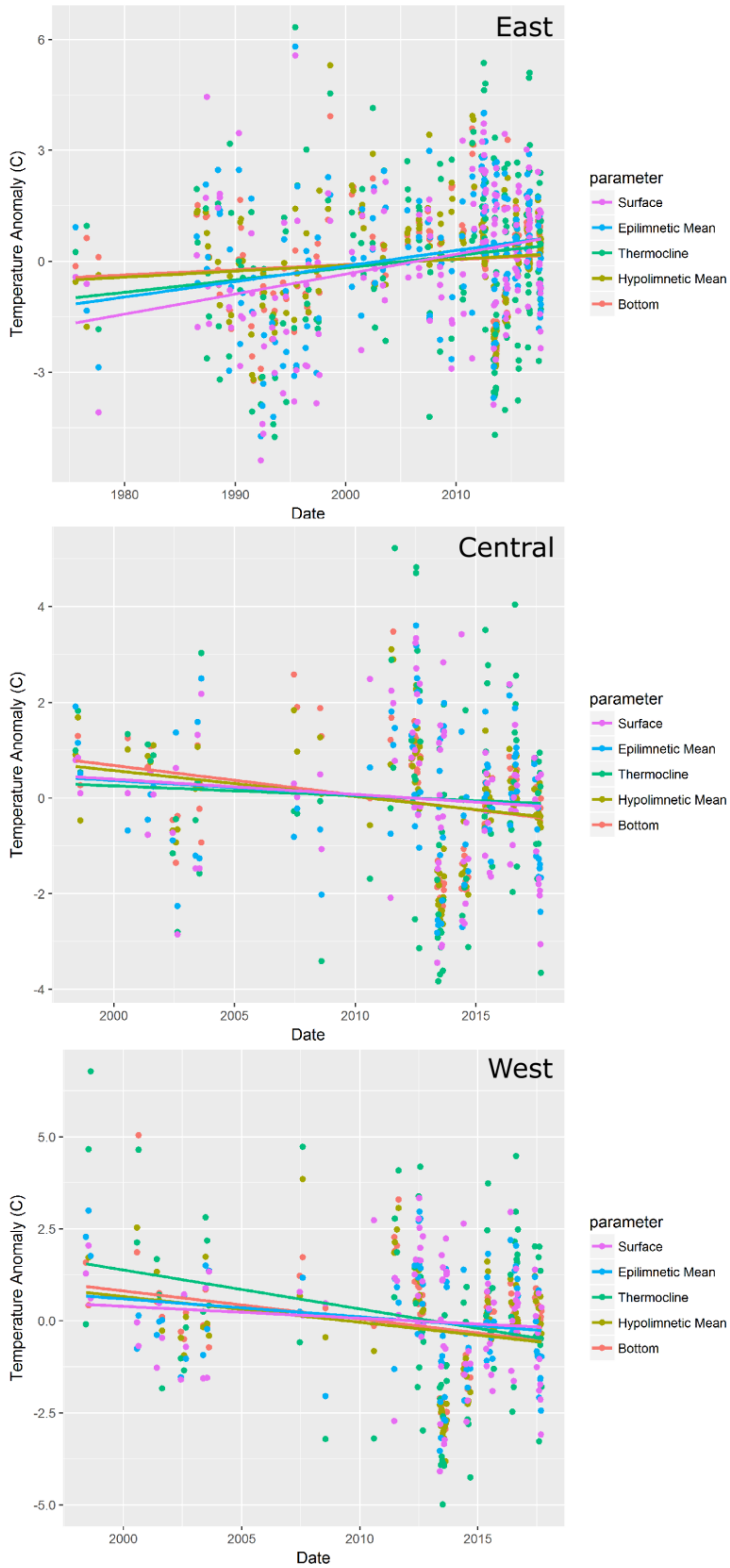

Figure 21. Long-term trends in temperature described as anomalies (deviation from the expected temperature), and calculated as the residuals of the sinusoidal models shown in Figure 20. Trends were assessed for multiple depth profiles.

Modeled Temperature Simulations

In addition to observed temperature trends over time, we reviewed the results of modeled temperature simulations for a time period in the past (1982 – 2000) and two time periods in the future (2041-2059 and 2081-2099, Figure 22). Projected surface water temperatures were based on the worst-case emission scenario (Winslow et al. 2017). Although there was not a significant warming trend during the historical time period, the average summer (July, August, and September) surface water temperature of Lac Courte Oreilles is projected to increase by on average 4.6ºC over a 100-year time frame. The average surface water temperature from 1982 – 2000 was 21.6ºC, and the average temperatures in the two future time periods were 24.1ºC and 26.1ºC. If these likely warming trends come to pass, oxythermal habitat for cold water fishes will decline.

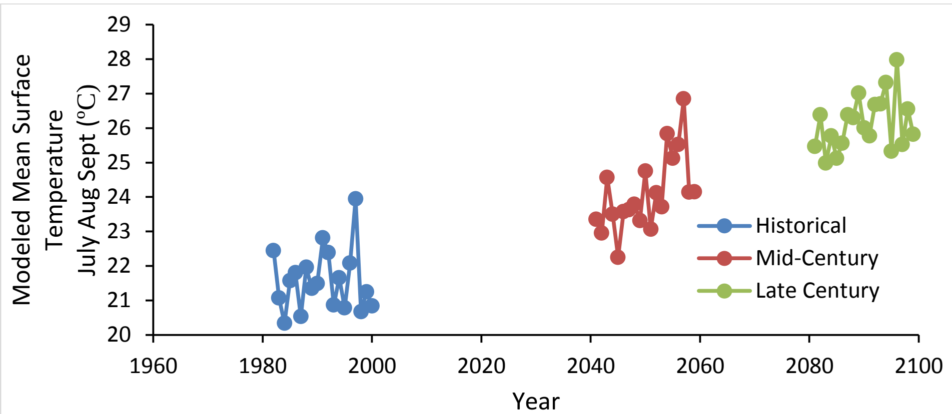

Figure 22. Modeled summer (July – September) surface water temperatures in Lac Courte Oreilles for 1 time period in the past and two time periods in the future.

5.10 SSC Recommendation for Main Basins

We do not recommend an SSC for the main basins of the lake, and instead recommend retaining the statewide TP criterion of 15 µg/L. This recommendation is based on the following line of reasoning.

Is phosphorus clearly causing the negative impacts to the coldwater fish community?

- ➔ **No.** Our analyses cannot verify that phosphorus is reducing the oxythermal layer and there are several plausible alternative factors not related to phosphorus that could be causing the negative impacts. Further research is recommended to better understand the mechanisms of oxygen depletion, which will help guide efforts to improve the two-story fishery habitat.

Would a phosphorus concentration lower than the statewide criterion of 15 µg/L reduce the negative impacts to the oxythermal layer and coldwater fishery?

- ➔ **Probably not.** Phosphorus concentrations ranged from 6.3 – 14.7 µg/L over the period of record, and HOD was unchanged. Even in the East Basin where there was a significant relationship between one measure of HOD and TP, HOD could be as high at 8 µg/L TP as at 14.7 µg/L TP. Given the additional causes of two-story fishery impacts described above, reduced phosphorus is not likely to significantly improve the two-story fishery habitat deficiencies.

Therefore, we cannot demonstrate any of the following: 1) the designated uses are not protected by the statewide phosphorus criterion, 2) a clear link between phosphorus concentrations and the protection of these designated uses, and 3) that scientific evidence demonstrates that a more-stringent phosphorus concentration is necessary to protect the designated uses.

6. SMALL BAYS

Small bays are not assigned separate designated uses from the main lake, unless they are significantly restricted from the main lake and exhibit different characteristics (such as Musky Bay, discussed below). State water quality criteria are designed to be measured and assessed at the deep part of the lake. Assessments using this approach represent the health of the lake as a whole, including any bays along the perimeter. There is no technical basis to assign a separate criterion for the small bays of Lac Courte Oreilles.

The court-approved settlement in this case stipulated that the bays be considered within this analysis. Therefore, we reviewed the limited amount of data that were available within these five bays. Although small bays would not typically be assessed separately from the main basins, we applied the same methodology for informational purposes. Because applying the metrics in this way is non-standard, the results should be interpreted in that light. The following information summarizes the available data for Stuckey Bay, Chicago Bay, Anchor Bay, Northeast Bay, and Brubaker Bay.

6.1 Phosphorus

Main findings:

- Total phosphorus was low in all four bays with data: Anchor Bay, Northeast Bay, Stuckey Bay, and Chicago Bay. Their mean phosphorus concentrations, ranging from 10.41 to 13.51, are lower than any of the statewide phosphorus criteria. There was not any data from Brubaker Bay.
- Annual average TP has not significantly changed over time in any of the bays. Note that TP in Stuckey Bay was high in 2000.

Total phosphorus data were provided by WDNR staff and the Lac Courte Oreilles Tribe. Although small bays would not typically be assessed separately from the main basins, we applied the same methodology for informational purposes and consistent with the court-approved settlement. Data collected from 2012-2016 were used to assess Anchor Bay, Northeast Bay, and Stuckey Bay. Data from 2003-2007 was used to assess Chicago Bay for this report because this was the most recent data available. There was not any data from Brubaker Bay. Note that three outliers were removed from analysis in Stuckey Bay (concentrations of 99, 110, and 260 µg/L TP). Two of these samples appeared to be bottom samples mislabeled as surface samples. This was a concern noted in additional samples, but only these three samples were extremely high.

Total phosphorus was low in all four bays with data. Their mean phosphorus concentrations, ranging from 10.41 to 13.51, are lower than any of the statewide phosphorus criteria, the lowest of which (for stratified lakes) is 15 µg/L (Table 13).

Table 13. Assessment of total phosphorus for the small bays of Lac Courte Oreilles.

WBIC	WATERS ID	Station Name	Dates reviewed	Mean Total Phosphorus (µg/L) (80% confidence interval)
2390800	15368	Anchor Bay (LCO-5)	2012-2016	12.15 (11.04-13.38)
2390800	15368	Northeast Bay (LCO-6)	2012-2016	12.15 (10.75-13.73)
2390800	15368	Stuckey Bay (LCO-1)	2012-2016	13.51 (12.39-14.73)
2390800	15368	Chicago Bay	2003-2007	10.41 (9.92-10.94)
2390800	15368	Brubaker Bay	No data	No data

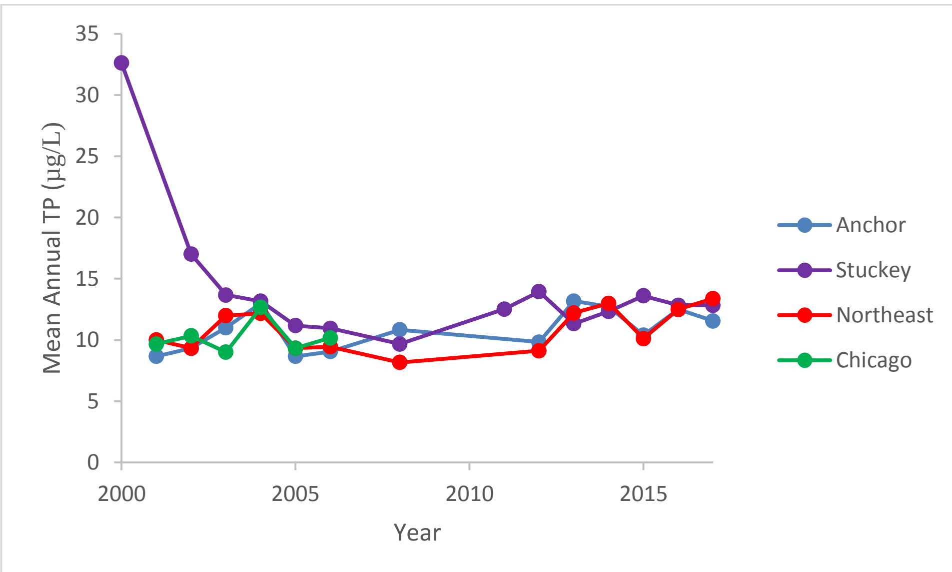

Figure 23. Annual mean total phosphorus over time in the small bays of Lac Courte Oreilles.

To analyze trends over time, we calculated the annual average total phosphorus (TP) concentrations from samples taken at < 2 m deep between June 1 and September 15. We used the same methods as we did for the main basins to calculate annual averages, which removed more outliers than the three that were removed for assessment. Small Bay data were available from 2000 to 2017. Simple linear regressions were performed predicting TP based on year for each station. TP has not significantly changed over time in any of the four bays analyzed (Figure 23). Note that TP was high in Stuckey Bay in the year 2000.

6.2 Chlorophyll *a*

Main findings:

- Chlorophyll *a* was low in all four bays with data: Anchor Bay, Northeast Bay, Stuckey Bay, and Chicago Bay. Each small bay has zero percent of days with moderate algae levels. Mean chlorophyll *a* for each of the small bays was ~2 µg/L. These are lower than any of the statewide chlorophyll *a* thresholds for aquatic life or recreation uses. There was not any data from Brubaker Bay.
- Therefore, TP does not need to be reduced from current concentrations in the small bays to protect for recreation and aquatic life uses as determined by chlorophyll *a* metrics.
- Chlorophyll *a* did not change significantly over time in any of the small bays.

Chlorophyll *a* data were provided by WDNR staff and the Lac Courte Oreilles Tribe. Data collected from 2012-2016 were used to assess Anchor, Northeast, and Stuckey Bays. The most recent chlorophyll *a* data available in Chicago Bay was from 2002 – 2006. No outliers were found.

At each of the four bays, the chlorophyll *a* data were very low when calculated for both recreation use and aquatic life use. In the recreation use assessment each small bay has zero percent of days with moderate algae levels (Table 14). For the aquatic life use assessment, the small bays' mean chlorophyll *a* was 1.73-2.32 µg/L (Table 15), which is far below any of the chlorophyll *a* thresholds.

Table 14. Small bay recreation use assessment for frequency of moderate algae levels.

WBIC	WATERS ID	Station Name	Dates reviewed	**Chlorophyll *a*** *(% summer days with moderate algae levels)*
2390800	15368	Stuckey Bay	2012-2016	0
2390800	15368	Anchor Bay	2012-2016	0
2390800	15368	Northeast Bay	2012-2016	0
2390800	15368	Chicago Bay	2003-2007	0
2390800	15368	Brubaker Bay	No data	No data

Table 15. Small bay aquatic life assessment for chlorophyll *a* concentrations.

WBIC	WATERS ID	Station Name	Dates reviewed	Mean Chlorophyll *a* (µg/L) (80% confidence interval)
2390800	15368	Stuckey Bay	2012-2016	2.32 (2.12-2.53)
2390800	15368	Anchor Bay	2012-2016	1.73 (1.59-1.88)
2390800	15368	Northeast Bay	2012-2016	2.11 (1.97-2.27)
2390800	15368	Chicago Bay	2002-2006	1.09 (0.66-1.79)
2390800	15368	Brubaker Bay	No data	No data

To analyze trends over time, we calculated annual average chlorophyll *a* concentrations from samples taken at < 2 m deep between July 1 and September 15. Annual averages were calculated separately for each of the small bays. Simple linear regressions were performed predicting chlorophyll *a* based on year for each station. Chlorophyll *a* did not change significantly over time at any of the bays (Figure 24).

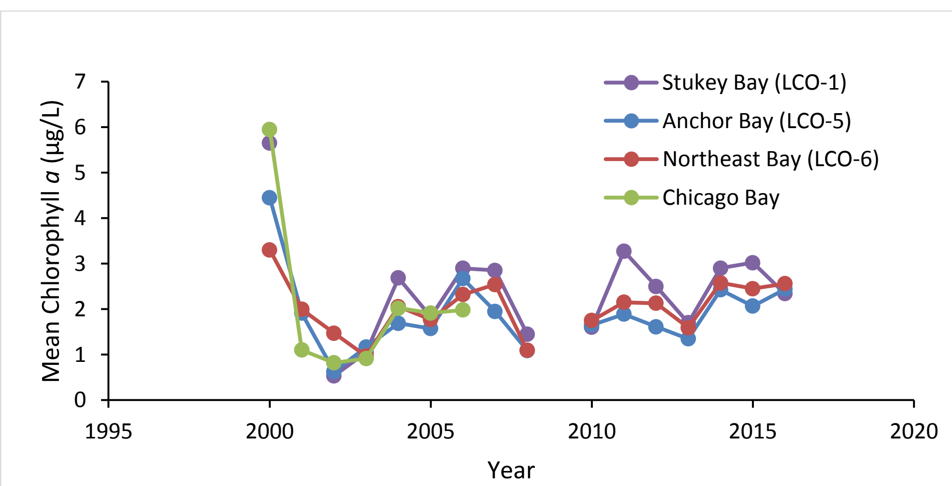

Figure 24. Annual mean chlorophyll *a* over time in the small bays of Lac Courte Oreilles.

6.3 Aquatic plants

Main findings:
The 2010 plant survey was used to assess the individual bays. Although this provides a somewhat limited dataset for each unit, the results for the bays are similar to those for the whole lake. Aquatic plant thresholds for Northern drainage lakes were applied for both the general condition assessment (attained if tolerant species ≤73%) and the phosphorus response assessment (attained if phosphorus-sensitive species are >51%).

- The plant community in each of the five bays attains the general condition threshold used to assess for response to a range of disturbances, with tolerant species present from 9 to 50% of sampling points in the various bays. It also attains the threshold that would indicate a response specific to phosphorus, with phosphorus-sensitive species present at 83-97% of sampling points in the various bays.
- Therefore, TP does not need to be reduced from current concentrations in the small bays to protect the aquatic plant community.

Protocols for aquatic plant surveys are described in section 5.3 for the main basins and the subsets of sampling points that were applied to each bay. To produce bay-specific information, we subset the sampling grid spatially, though this procedure results in a smaller-than-recommended sample size; results should be interpreted with some caution. Using this approach, the aquatic plant community attained both the assessment for general condition (MAC) and for phosphorus response (MAC-P) (Table 16).

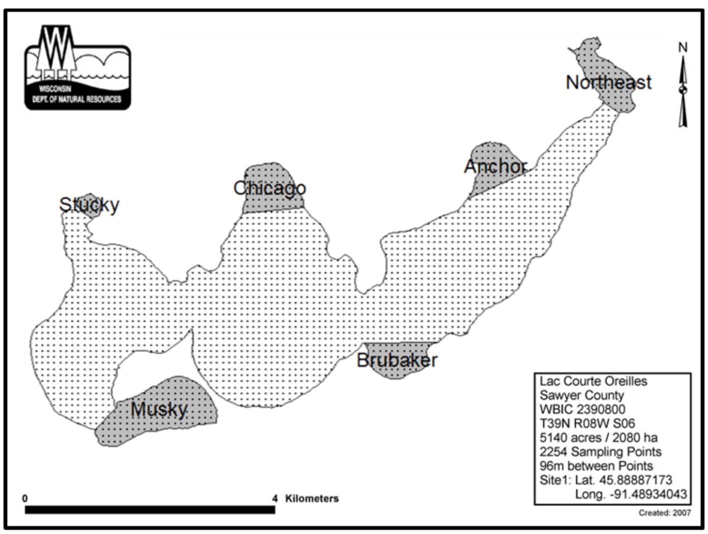

Figure 25. Lac Courte Oreilles aquatic plant sampling grid and bay subsets.

Table 16. Draft macrophyte condition assessment decisions for small bays based on aquatic plant data collected in 2010. The aquatic plant metrics in this table are proposed in ch. NR 102 revisions.

	General Condition Assessment (MAC)			**Phosphorus Response Assessment (MAC-P)**		
	Threshold (attains if…)	% Tolerant	MAC Status	Threshold (attains if…)	% Phos.-sensitive	MAC-P Status
Stuckey Bay	Tolerant species ≤73%	50%	Attains	Phosphorus-sensitive species >51%	83%	Attains
Chicago Bay		35%	Attains		94%	Attains
Anchor Bay		21%	Attains		89%	Attains
Northeast Bay		33%	Attains		97%	Attains
Brubaker Bay		9%	Attains		91%	Attains

6.4 SSC Recommendation for small bays

There is no technical basis to assign a separate criterion for the small bays of Lac Courte Oreilles. We do not recommend that a phosphorus criterion be applied to the small bays that is different from the overall lake, for two main reasons:

- Standardized methods for assessing health of small bays independent from the overall lake are not yet available, and methods for developing appropriate criteria for small bays are also unavailable.
- Each of the four small bays with data exhibit very low chlorophyll levels, attaining even the most stringent thresholds, and a healthy aquatic plant community. There is no justification for treating these bays differently from bays on other lakes in the state.

As a general matter, the criterion applied to the main basins in a lake should be considered inclusive of the small bays, whether that be the statewide criterion or an SSC. Assessment of that criterion should follow standard protocols for all lakes, using measurements only at the deep hole(s), not samples within the small bays. In this case, the statewide phosphorus criterion for Lac Courte Oreilles is protective of the designated uses of the lake, and therefore also protective of the small bays.

7. Musky Bay

In Musky Bay, residents are concerned about both aquatic life habitat issues (low dissolved oxygen affecting musky spawning) and recreation issues (inhibition of navigation due to abundance of curly-leaf pondweed and algal mats). These specific concerns, however, are difficult to assess using existing information and methods available to the department. In order to establish a phosphorus SSC, we must demonstrate 1) that there is an impairment of uses, 2) a clear link between the impairments and phosphorus concentrations, and 3) that a more-stringent phosphorus concentration is needed to attain those uses. While we cannot directly measure or assess the residents' specific concerns with the data and methods available to us, we evaluated whether phosphorus concentrations are having a general impact on aquatic life and recreation by using standard protocols for evaluating chlorophyll *a* concentrations and aquatic plant condition, consistent with the proposed rule. Both metrics indicated healthy conditions and did not warrant a site-specific phosphorus criterion for Musky Bay. However, these conclusions do not preclude future studies that may directly the condition of musky spawning habitat, curly-leaf pondweed and algal mat abundance and establish their relationships to pollutants and nutrients, including phosphorus.

A summary of the attainment status for Musky Bay for each of the recreation and aquatic life use thresholds contained in the proposed revisions to ch. NR 102 is shown in Table 17. These are described in detail in this section.

Table 17. Summary of attainment status for Musky Bay (2012-2016). The metrics in this table are proposed in ch. NR 102 revisions.

Designated Use	Metric (proposed in revisions to ch. NR 102)	Assessment Status
Recreation	Chlorophyll *a* (% summer days with moderate algae levels)	Attains
Aquatic Life	Chlorophyll *a* concentration	Attains
	Macrophytes – General condition	Attains
	Macrophytes – Phosphorus response	Attains (did not attain in 2011 and 2012)

7.1 Phosphorus

Main findings:

- Musky Bay's summer mean phosphorus concentration is 29.53 µg/L, which attains the currently applicable TP criterion of 40 µg/L.
- Musky Bay's annual average TP does not exhibit a significant trend over time when looking at the entire data record from 2000 to 2017. However, prior to 2010 TP was more variable and exceeded the criterion in some years. After 2012, TP was less variable and declined through 2017.

Total phosphorus data were provided by WDNR staff and the Lac Courte Oreilles Tribe. Data collected on Lac Courte Oreilles from 2012-2016 were used in the 2018 assessments. Calculations and data selection methods are outlined in the 2018 Wisconsin Consolidated Assessment and Listing Guidance (WisCALM) document.

In Musky Bay the total phosphorus data were clearly below the criterion for recreation and aquatic life uses (Table 18).

Table 18. Total phosphorus (TP) assessment data for Musky Bay (2018).

				Total Phosphorus (µg/L)		
WBIC	WATERS ID	Station Name	Natural Community	TP Crit. (Rec. & Aqu. Life)	Mean (80% confidence interval)	Recreation & Aquatic Life Status
2390800	1850472	Musky Bay (MB-1)	Shallow Lowland	40	29.53 (27.10-32.19)	Clearly Attains

To analyze trends over time, we calculated the annual average TP concentrations from samples taken at < 2 m deep between June 1 and September 15. We used the same methods as we did for the Main Basins to calculate annual averages. Musky Bay data were available from 2000 to 2017. Simple linear regressions were performed predicting TP based on year for station MB-1. TP has not significantly changed over time at the Musky Bay station (Figure 26). TP varied greatly from 2001 – 2009 with average TP ranging from 25.5 to 49.6 in consecutive years. Since 2012, TP has gradually declined from 41.6 to 23.9 in 2017.

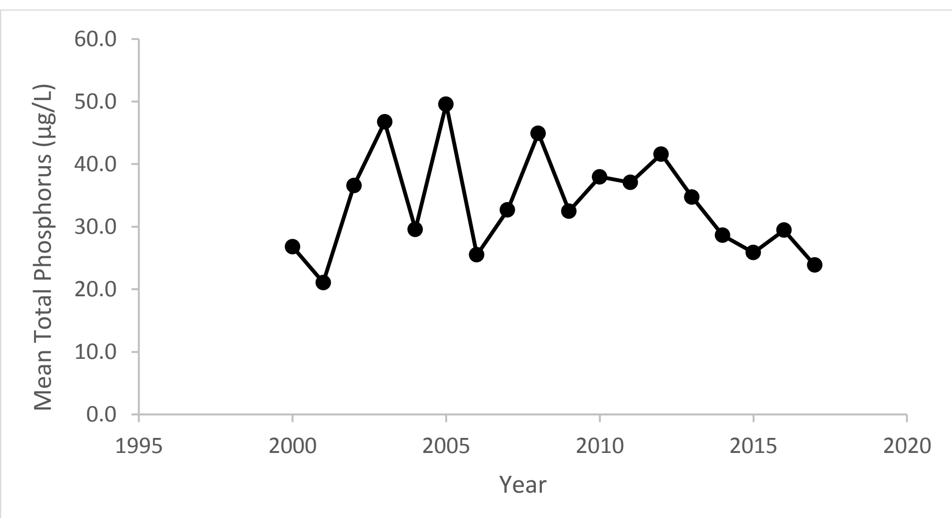

Figure 26. Trend over time of mean annual total phosphorus in Musky Bay.

7.2 Chlorophyll *a*

Main findings:

- Musky Bay attains the chlorophyll *a* thresholds for recreation and aquatic life for unstratified drainage lakes. Musky Bay's mean chlorophyll *a* concentration is 5.75 µg/L (attained if <27 µg/L). It has ~6% of summer days with moderate algae levels (attained if <25% of summer days have moderate algae levels).
- Chlorophyll *a* was still well below the threshold in years when TP exceeded the current criterion applied to Musky Bay of 40 µg/L.
- Therefore, 40 µg/L TP is protective of both the recreation and aquatic life chlorophyll *a* metrics.
- Chlorophyll *a* in Musky Bay did not exhibit a significant trend over time, though it did fluctuate over time with changing TP concentrations.
- Chlorophyll *a* is higher in Musky Bay than elsewhere in Lac Courte Oreilles.

Chlorophyll *a* data were provided by WDNR staff and the Lac Courte Oreilles Tribe. Data collected in Musky Bay from 2012-2016 were used in the 2018 assessments. Calculations and data selection methods are outlined in the 2018 Wisconsin Consolidated Assessment and Listing Guidance (WisCALM) document.

Musky Bay "Clearly Attains" the chlorophyll *a* thresholds for both recreation use (Table 19) and aquatic life use (Table 20). The recreation use threshold for shallow lowland drainage lakes is attained if less than 25% of summer days have moderate algae levels, defined as >20 µg/L chl *a*. Musky Bay has moderate algae levels on 2% of summer days (Table 19). The mean chlorophyll *a* concentration in Musky Bay is 6 µg/L, which is well below the aquatic life threshold of 27 µg/L (Table 20).

Table 19. Musky Bay recreation use assessment data (2018) for frequency of moderate algae levels. Chlorophyll *a* thresholds in this table are proposed in ch. NR 102 revisions.

				Chlorophyll *a* (% summer days with moderate algae levels)		
WBIC	WATERS ID	Station Name	Natural Community	Chl-a Thresh. (Rec.)	Mean (80% confidence interval)	Recreation Status
2390800	1850472	Musky Bay (MB-1)	Shallow Lowland	25%	1.9 (0.2-9.4)	Clearly Attains

Table 20. Musky Bay aquatic life use assessment data (2018) for chlorophyll *a* concentrations. Chlorophyll *a* thresholds in this table are proposed in ch. NR 102 revisions.

				Chlorophyll *a* (µg/L)		
WBIC	WATERS ID	Station Name	Natural Community	Chl-a Thresh. (Aqu. Life)	Mean (80% confidence interval)	Aquatic Life Status
2390800	1850472	Musky Bay (MB-1)	Shallow Lowland	27	5.75 (4.50-7.34)	Clearly Attains

As expected, chlorophyll *a* is higher in years with high TP (Figure 27). There were four years in which the mean annual TP was greater than the current criterion of 40 µg/L (2003, 2005, 2008, and 2012). Despite high phosphorus, mean annual chlorophyll *a* was still well below the aquatic life criterion of 27 µg/L and even below the definition of moderate algae levels at 20 µg/L chl *a*. In general, chlorophyll *a* for a given phosphorus concentration is lower than expected given the statewide relationship between phosphorus and chlorophyll *a* (Figure 27). Thus, the standard statewide TP criterion for shallow lowland lakes is protective of the chlorophyll *a* aquatic life and recreation uses.

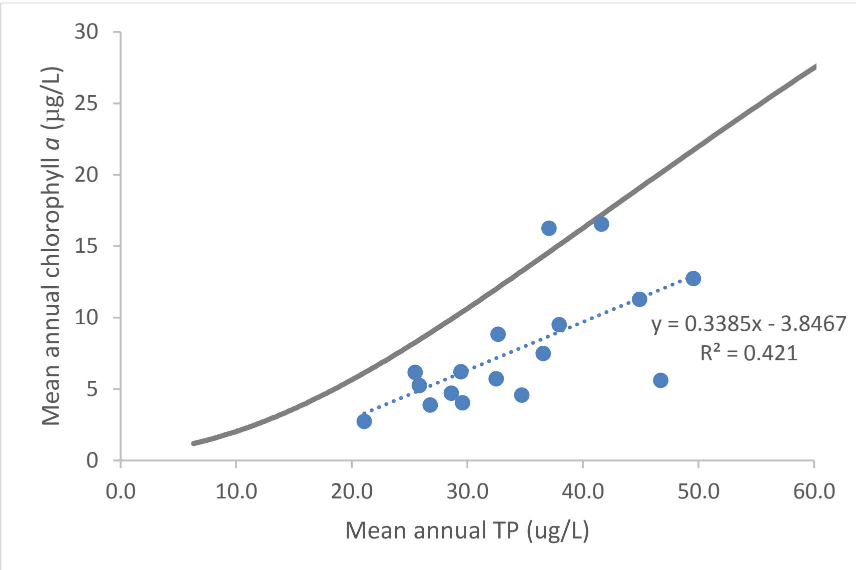

Figure 27. Relationship between annual mean TP and chlorophyll *a* in Musky Bay (station MB-1, blue points and blue dashed regression line) compared to the statewide relationship (gray line).

To analyze trends over time, we calculated annual average chlorophyll *a* concentrations from samples taken at < 2 m deep between July 1 and September 15. Simple linear regressions were performed predicting chlorophyll *a* based on year for each station. Chlorophyll *a* in Musky Bay did not exhibit a significant trend over time, though it did fluctuate over time with fluctuating TP concentrations (Figure 28). Chlorophyll *a* is higher in Musky Bay than in the main basins or other bays.

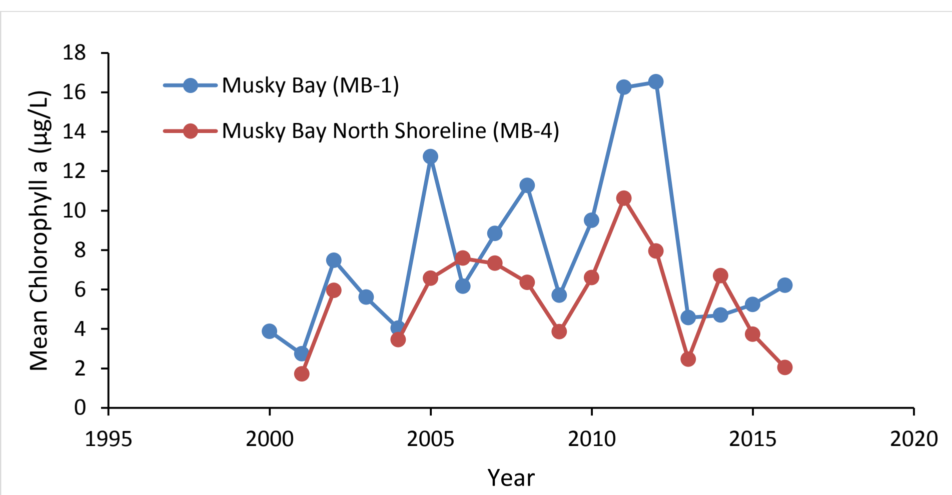

Figure 28. Annual mean chlorophyll *a* over time in Musky Bay.

Algal mats
In conjunction with dense plant growth, periodic algal mats in Musky Bay reportedly impede navigation (recreation). The department's standard assessment methods do not quantify the presence or extent of algal mats. Chlorophyll *a* is measured within the top 2 meters of the water column to quantify the abundance of phytoplankton, and algal mats are specifically avoided. To develop a site-specific phosphorus criterion based on algal mats, two pieces of information are needed: 1) a quantitative measure of algal mat abundance and 2) a demonstrated phosphorus concentration that would limit the extent of algal mats. Neither of these are available at this time.

7.3 Aquatic plants

Main findings:

- Plant data collected with high spatial resolution in Musky Bay in 2007 and in all years 2010 – 2016 revealed that Musky Bay attained the general condition threshold in all years (attained if tolerant species ≤73%). In 2011 and 2012, it failed to attain the plant phosphorus response threshold (attained if phosphorus-sensitive species >51%), indicating there may have been a short-term impairment that could be related to nutrient levels. Since then (2013-2016), plants consistently attained the phosphorus response thresholds.
- The available data suggest that 40 µg/L is protective of aquatic plants in Musky Bay. Three aquatic plant surveys attained the phosphorus response indicator when phosphorus was 32.7 – 38.0 and two aquatic plant surveys did not when phosphorus was 37.1 - 41.6 µg/L.
- Musky Bay was listed as impaired for high densities of curly-leaf pondweed, an invasive aquatic plant, in 2012. The number of acres treated with herbicide has declined in recent years, suggesting that curly-leaf pondweed is not as pervasive as it was in 2010-2012. The curly-leaf pondweed population likely responds to the combined influence of a large number of environmental variables, and we currently lack sufficient understanding of the relationship between curly-leaf pondweed biomass and water column nutrient concentration to use curly-leaf pondweed density as an indicator of nutrient impairment. In addition, the active management of curly-leaf pondweed may hamper our ability to discern the specific relationship between environmental factors and the present population.
- The density and biomass of aquatic plants and their relationship with phosphorus could not be evaluated with available data or methods.

Aquatic plant survey methods are described in section 5.3. Musky Bay was assessed as part of the 2010 whole-lake assessment, using a subset of sampling points from the overall assessment (Figure 6). Using this analysis Musky Bay attained both the assessment for general condition (MAC) and the assessment for phosphorus response (MAC-P). Musky Bay, like the whole lake, falls into the Northern Drainage category for this assessment. Results are shown in Table 21.

Table 21. Draft macrophyte condition assessment decision for Musky Bay based on aquatic plant data collected in 2010. The aquatic plant metrics in this table are proposed in ch. NR 102 revisions.

	General Condition Assessment (MAC)			Phosphorus Response Assessment (MAC-P)		
	Threshold (attains if…)	% Tolerant	MAC Status	Threshold (attains if…)	% Phosphorus sensitive	MAC-P Status
Musky Bay	Tolerant species ≤73%	67%	Attains	Phosphorus-sensitive species >51%	68%	Attains

Following the analysis of the 2010 whole-lake survey, WDNR obtained data from external partners on Musky Bay collected in 2007 and all years from 2010 to 2016. The surveyors applied the baseline monitoring protocol, using a sampling grid of 394 points, which is more than recommended by the baseline protocol (Figure 29). Surveyors collected data on aquatic plant presence/absence at all points of this grid.

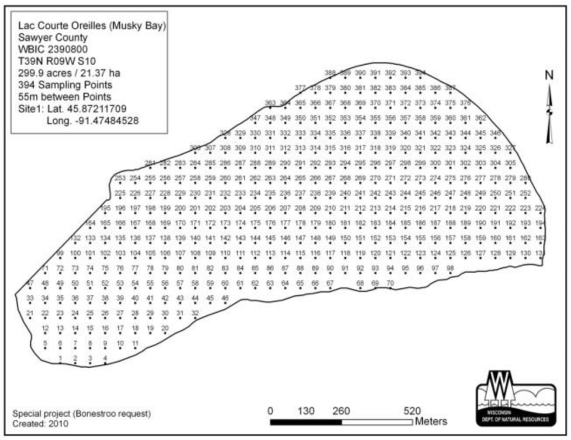

Figure 29. Musky Bay with aquatic plant sampling grid (394 Sampling points).

MAC and MAC-P assessments were calculated on Musky Bay following Mikulyuk et al. (2017). Echoing patterns found lakewide, the assessments most often met established thresholds (Table 22). However, in 2011 and 2012, the population of phosphorus-sensitive species declined slightly below the threshold, providing some evidence that the aquatic plant community was impacted during those two years. Since that time both plant thresholds have been attained.

Table 22. Draft macrophyte condition assessment decisions for Musky Bay using data collected on a sampling grid specific to Musky Bay. For reference, mean annual TP concentrations in Musky Bay are also listed here.

	General Condition Assessment (MAC)			**Phosphorus Response Assessment (MAC-P)**			**Mean Annual TP (µg/L)**
Musky Bay Year	Threshold (attains if…)	% Tolerant	MAC Status	Threshold (attains if…)	% Phosph.-Sensitive	MAC-P Status	
2007	Tolerant species ≤73%	48%	Attains	Phosphorus-sensitive species >51%	97%	Attains	32.7
2010		67%	Attains		68%	Attains	38.0
2011		60%	Attains		42%	*Does not attain*	37.1
2012		25%	Attains		42%	*Does not attain*	41.6
2013		60%	Attains		63%	Attains	34.7
2014		53%	Attains		60%	Attains	28.6
2015		45%	Attains		66%	Attains	25.9
2016		42%	Attains		84%	Attains	29.4

In 2011 and 2012, the biodiversity of the plant community was lower relative to other years. This means that in 2011 and 2012, there were fewer species recorded, and abundance patterns were skewed toward a dominant few species. In addition, the fern-leaf pondweed (*Potamogeton robbinsii*) population decreased substantially in 2010 and did not recover. This species tends to have lax stems and, though caulescent and capable of extending up into the water column, is often found lying horizontally on the substrate. Compared to other wide-leafed submergent plants, fern-leaf pondweed is relatively sensitive to shading and changes in water clarity. Natural, anthropogenic, stochastic or observer differences are all candidate drivers for the observed community shift in 2011 and 2012. It does coincide with the years when large areas of Musky Bay were treated with herbicide to control invasive curly-leaf pondweed (Table 24). Although the decrease in fern-leaf pondweed was sustained, biodiversity and phosphorus-sensitive plant species recovered after 2012 (Table 23, Figure 30).

Table 23. Information on biodiversity by year. Number of species is the simple count of species observed, evenness describes how similar each species is in terms of relative abundance, and Shannon's H index combines number of species and evenness into a single index of biodiversity. Note that Shannon's H index is lowest for years 2011 and 2012.

Musky Bay Year	Number of species	Evenness	Shannon's H index
2007	26	0.68	2.2
2010	19	0.73	2.2
2011	26	0.59	1.9
2012	22	0.56	1.7
2013	25	0.66	2.1
2014	25	0.66	2.1
2015	27	0.70	2.3
2016	30	0.73	2.5

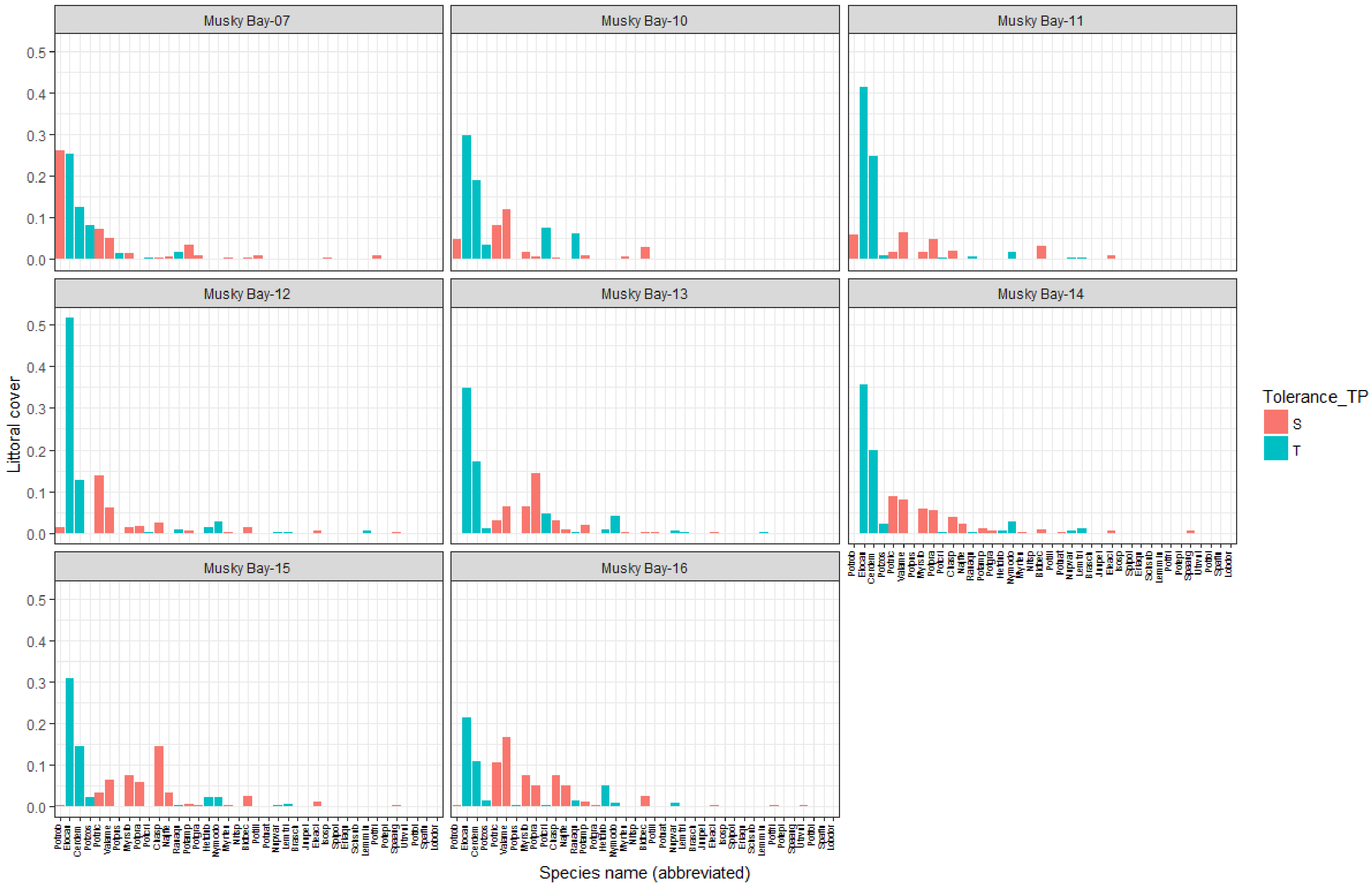

Figure 30. Littoral cover by species and across years (2007 in upper left). General shape of the abundance distribution is consistent across most years, with some notable changes in individual species abundance patterns (e.g. fern-leaf pondweed; *Potamogeton robbinsii*).

Plant abundance and curly-leaf pondweed

Although the composition of the aquatic plant community in Musky Bay is generally healthy and includes species that are not indicative of degradation, lake users have expressed significant concern over the amount (or abundance) of aquatic plants in the bay. Curly-leaf pondweed (*Potamogeton crispus*), an invasive plant that reaches peak abundance early relative to other Wisconsin plant species, reportedly interferes with navigation and recreational activities.

Musky Bay was listed as impaired for recreation due to curly-leaf pondweed in 2012 with phosphorus listed as the pollutant. Phosphorus was indeed high in 2012, but we do not have enough data on curly-leaf pondweed abundance over time to establish a relationship with phosphorus. Curly-leaf pondweed is a cosmopolitan species that tends to do well in lakes with high nutrients, but the presence of curly-leaf pondweed alone does not indicate nutrient impacts. The curly-leaf pondweed population likely responds to the combined influence of a large number of environmental variables, and we currently lack sufficient understanding of the relationship between curly-leaf pondweed biomass and water column nutrient concentration to use curly-leaf pondweed density as an indicator of nutrient impacts. A study of Minnesota lakes indicated that factors other than phosphorus can also influence curly-leaf pondweed abundance, such as water temperature and snow cover (Heiskary and Valley 2012).

Our mid-summer aquatic plant surveys occur after peak curly-leaf pondweed abundance in spring, but we do have a record of the number of acres that were treated with herbicide to reduce curly-leaf pondweed abundance in Musky Bay (Table 24). We assume that the number of acres treated approximates the extent of this invasive species each year. If this is the case, curly-leaf pondweed was extensive in 2010-2012, the years contributing to the 2012 curly-leaf pondweed impairment listing. Since then, the number of acres treated is much lower, suggesting that curly-leaf pondweed is still present, but less extensive.

Table 24. Acres of curly-leaf pondweed treated with herbicide in Musky Bay over time.

Year	Acres
2009	7.0
2010	79.9
2011	96.0
2012	65.0
2013	29.0
2014	3.0
2015	25.0
2016	25.0
2017	9.0

Currently, the department does not have procedures available for assessing 1) abundance of plants, 2) what constitutes a healthy level of abundance for aquatic life, 3) what level of abundance impairs recreation, or 4) how much phosphorus influences curly-leaf pondweed abundance compared to other factors. Therefore, we were not able to assess and report on plant abundance in the bay. While the department recognizes that recreational issues are a major concern for residents, neither of our available indicators of phosphorus impairment, chlorophyll *a* and aquatic plants, indicate a phosphorus impairment.

7.4 Paleolimnology

Main findings:

- Prior sediment core studies indicate nutrient enrichment has been occurring since the 1930s. Periods in the 1960s, 1970s, and late 1990s also contributed to nutrient enrichment in the lake.
- Natural background concentrations of TP are estimated at 19 and 29 µg/L TP, based on two sediment core analyses, but these estimates are approximate. The natural background concentration represents the lowest level at which an SSC might be set.

The sediment can impart information about the lake's long-term history by examining changes in the species composition of diatoms that settled in the sediment over time. In 1999, two sediment cores were collected in Musky Bay. The results of this study can be reviewed in detail (Fitzpatrick et al. 2003, Garrison and Fitzgerald 2005), but some of the most relevant findings are summarized here.

Musky Bay has become more eutrophic since approximately 1930. There are several lines of evidence of eutrophication:

1. Increased aluminum indicates that soil erosion began ca. 1930.
2. Nutrient levels started to increase soon after 1930 as signaled by:
    a. Increasing biogenic silica (indicating higher abundance of diatoms),
    b. Increasing abundance of some benthic diatom taxa (ex. *Staurosira* sp.),
    c. Decreasing abundance of planktonic diatom taxa (ex. *Achnanthidium minutissima*, *Navicula pseudoventralis*, *Aulacoseira ambigua*).
3. Further nutrient enrichment occurred later in the record:
    a. Starting in 1960, *Staurosira construens va. Binodis* increased,
    b. Starting in 1970, *Aulacoseira ambigua* decreased.
4. Indicators of fertilizers started ca. 1996:
    a. Calcium:Aluminum abruptly increases,
    b. Potassium:Aluminum abruptly increases,
    c. A diatom indicative of algal mats increases (*Fragilaria capucina*).

Paleolimnology can sometimes be used to estimate natural background phosphorus concentrations prior to significant impacts from Euro-American settlement (circa mid-1800s). However, the diatom community in the Musky Bay cores was dominated by taxa that are phosphorus generalists, making it difficult to accurately estimate the natural background phosphorus concentration of Musky Bay. Natural background estimates of total phosphorus based on diatom taxa from 2 cores in Musky Bay were 19 µg/L and 29 µg/L, but these estimates have a high degree of uncertainty (Garrison 2014).

7.5 SSC Recommendation for Musky Bay

- We do not recommend setting a site-specific phosphorus criterion lower than the applicable statewide criterion of 40 µg/L for Musky Bay. Available data include a range of phosphorus concentrations in Musky Bay that allows us to directly observe how it responds to high phosphorus concentrations. Our existing assessment methods showed that when phosphorus was greater than 40 µg/L, chlorophyll *a* still indicated healthy conditions. The available data, suggest that 40 µg/L is protective of aquatic plants as well. Three aquatic plant surveys attained the phosphorus response indicator when phosphorus was 32.7 – 38.0 and two aquatic plant surveys did not when phosphorus was 37.1 and 41.6 µg/L.
- Therefore, we cannot currently demonstrate any of the following: 1) the designated uses are not protected by the statewide phosphorus criterion, 2) a clear link between phosphorus concentrations and protection of these designated uses, and 3) that scientific evidence demonstrates that a more-stringent phosphorus concentration is necessary to protect the designated uses.
- We recommend delisting Musky Bay from the impaired waters list. In 2012, when Musky Bay was listed for high curly-leaf pondweed abundance with phosphorus as the pollutant, both TP and the plant metrics indicated that the lake was impaired. Now, at 29.53 µg/L, TP clearly attains the criterion of 40 µg/L. Treatment for curly-leaf pondweed has been effective in reducing its presence. Chlorophyll *a* attains both the recreation and aquatic life thresholds, and aquatic plants indicate that Musky Bay is in good condition.
- If observation or additional information indicate that spawning habitat for muskies, algal mats, and aquatic plant biomass are still problematic in Musky Bay, we recommend developing a monitoring program that quantifies these stress signals. In addition, phosphorus and other potential factors should be monitored at the same time to determine if there is a link between phosphorus and each of these variables. A cross-lake comparison and review of the literature may also help to establish expectations for each of these variables and their relationship to phosphorus.

8. Work in Progress

We recognize that concerns remain for the health of Lac Courte Oreilles and its fishery, and DNR staff expect to continue working with stakeholders to determine the main causes of coldwater fishery impacts and improve the quality of the lake. Meanwhile, DNR has several related efforts underway:

- DNR is currently undertaking three different rulemakings, all of which would apply to Lac Courte Oreilles if they are promulgated as currently proposed.
  - Rule package WT-25-13 contains a provision to establish a statewide oxythermal habitat standard for two-story fishery lakes.
  - Rule package WT-23-13 proposes establishing biocriteria and phosphorus response indicators. These include chlorophyll *a* criteria for recreation and aquatic life uses, and aquatic plant biocriteria for the aquatic life use.
  - Rule package WT-17-12 proposes establishing standard protocols for development of SSC.
- DNR has proposed in their 2018 draft Section 303(d) impaired waters list that the main basins of Lac Courte Oreille be listed as impaired in 2018 for not meeting the designated cold water use due to low dissolved oxygen. The draft list will be submitted to U.S. EPA in April 2018.
- DNR is in discussion with COLA and the Tribe regarding a habitat improvement project using dredging of sediments to improve musky spawning in Musky Bay.
- There are various avenues of potential future study which could help to investigate root causes, which may be eligible for state or federal grant funding.

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