Evaluation of the water clarity: Interaction of epilimnion and metalimnion in regard to bioavailable phosphorus, chlorophyll, and zooplankton.

Lake Owen, Bayfield County, WI

Analysis by: Ecological Integrity Service and Harmony Environmental

Abstract

Lake Owen, Bayfield County Wisconsin is classified as an oligotrophic lake by the Wisconsin DNR. Historically, the lake has exhibited high water clarity. The interaction of the epilimnion with the metalimnion in relationship to nutrients (in the form of bioavailable phosphorus), chlorophyll-a and the resulting Secchi depth (transparency) were evaluated. The possibility of zooplankton grazing on phytoplankton was also analyzed by enumeration. The degree of stratification was determined using temperature, dissolved oxygen and specific conductance profiles. Schmidt's Stability Index, stratification index and the Wedderburn number were all calculated to determine the degree of stratification. The thermocline depth, top and bottom borders of metalimnion were also evaluated. Water samples were collected twice monthly from May until late September at 0-2 meters and 4-9 meters in one-meter intervals and monthly in the hypolimnion and analyzed for soluble reactive phosphorus (SRP) and chlorophyll-a . Zooplankton were enumerated from 2-10 meters in 2-meter intervals twice per month, June through September. The data suggests that Lake Owen is strongly stratified from June until late October with little to no mixing and little to no fluxing of phosphorus from the hypolimnion. The chlorophyll-a was highest in May (while the soluble reactive phosphorus was below detection) and consistently higher in the metalimnion than in the epilimnion during the entire growing season. These data suggest that phosphorus limits phytoplankton growth. Chlorophyll-a decreased each month while phosphorus increased in June and then decreased during the remainder of the growing season. Data suggest there was an external load of SRP, possibly from conifer pollen and a large storm event in late June. Zooplankton counts increased significantly in August and September. The TSI for phosphorus was higher than chlorophyll and Secchi depth, from June-Sept demonstrating zooplankton grazing and phosphorus re-cycling by zooplankton.

Introduction

This report analyzes the interaction between the epilimnion and the metalimnion layers in regard to bioavailable phosphorus, chlorophyll production and water clarity in Lake Owen, Bayfield County Wisconsin.

Lake Owen is located in Bayfield County Wisconsin. It covers an area of 1268 acres, has a mean depth of 26.5 feet and a maximum depth of 95 feet. The lake is long and narrow, with a narrow littoral zone throughout most of the lake. Although is more than six miles long, due to its shape and being heavily forested, the fetch is short which limits the wind shear that can lead to mixing in the lake.

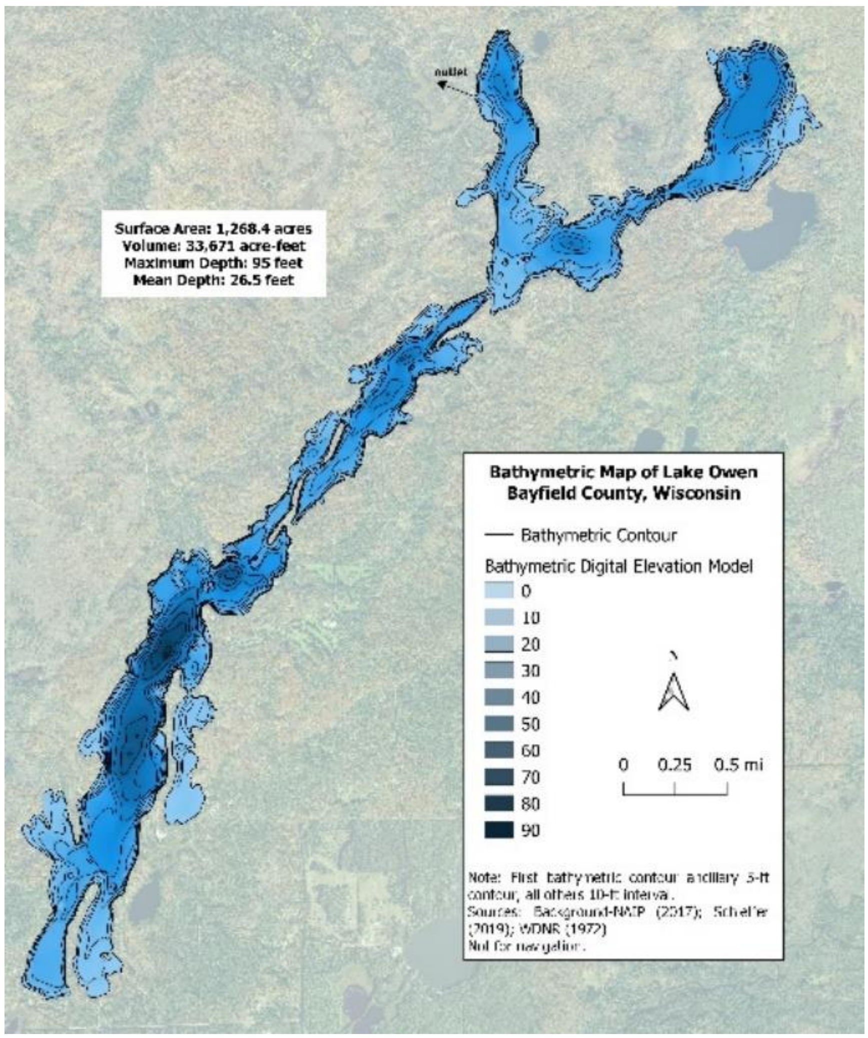

Figure 1: Bathymetry map of Lake Owen-2019.

Lake Owen is classified as oligotrophic by the Wisconsin Department of Natural Resources. Measured near-surface and upper epilimnion phosphorus concentrations support this classification, resulting in low chlorophyll-a concentrations and high Secchi disk readings, which are consistent with an oligotrophic state. However, the hypolimnion in Lake Owen is high in phosphorus concentration, approaching 400 ug/L (Lake Owen Comprehensive Management Plan, 2015). This is more typical of a eutrophic lake.

In 2013-14, a data analysis of Lake Owen in Bayfield County Wisconsin concluded that the lake had exceptional water clarity, with low phosphorus and chlorophyll-a concentrations (Lake Owen Comprehensive Management Plan, 2015). From the 2013-14 data, it was established that Lake Owen productivity is limited by phosphorus and the lake remains stratified for most all of the growing season. The hypolimnion consistently had a high concentration of phosphorus, similar to a more eutrophic lake, so it was assumed that phosphorus diffused into the epilimnion (top layer) where it was available for algae production. Water clarity in Lake Owen was dictated by phytoplankton (algae) productivity. Algae productivity was measured by chlorophyll-a concentration. It was also assumed that phytoplankton (algae) production was highest near the metalimnion and that zooplankton are likely grazing on algae, leading to increased water transparency. There was limited chemical data collected in and near the metalimnion in this analysis.

Phytoplankton are commonly referred to as algae. In the limnetic (open water) zone it is the phytoplankton that will reduce water clarity. Not all algae are technically phytoplankton as algae can exist in other forms. Phytoplankton are green and produce chlorophyll, so concentration of chlorophyll-a is used to represent the amount of phytoplankton produced. There are two forms of chlorophyll; a and b. Typically, chlorophyll-a is the one measured.

For ease of common reference, the term "algae" will be referring to phytoplankton in this report.

The 2015 management plan recommended an in-depth study of the food web to further understand the impact zooplankton have on algae and water clarity. Since the data in 2013-14 seemed to indicate that the limitation of phosphorus was a more likely source of high water clarity than zooplankton grazing, this 2019 analysis was designed to provide a larger data set to evaluate the interaction of phosphorus, algae and transparency in regard to the stratification, mobilization of phosphorus, and algae production. In addition, the 2019 data set could be used for further studies in internal and external loading. This analysis is planned for 2020.

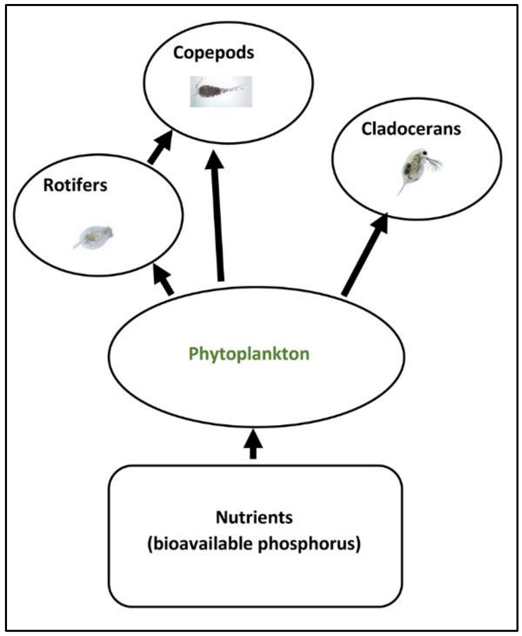

Figure 2: Trophic relationship in the limnetic zone.

The 2018 Lake Protection Grant application included a proposal to study the food web in Lake Owen. The hypothesis was that the water clarity may largely be based on zooplankton grazing on algae, limiting productivity and resulting in high water clarity. This hypothesis is plausible, but the historical water quality data strongly supports that phosphorus is limiting algae production. This is because when comparing the Trophic State Index (TSI) for total phosphorus, chlorophyll-a and Secchi depth, they were nearly the same throughout the growing season. If zooplankton were grazing enough to limit algae productivity, the phosphorus TSI would be expected to be higher than the TSI based on chlorophyll-a and Secchi depth. In this situation (TP TSI> chlorophyll-a and Secchi TSI) zooplankton would be reducing algae and reducing light attenuation (increasing water clarity) from levels expected at the higher phosphorus levels.

TSI values:
<40 = oligotrophic
40-50 = mesotrophic
50-60 = mild eutrophic
60+ = eutrophic

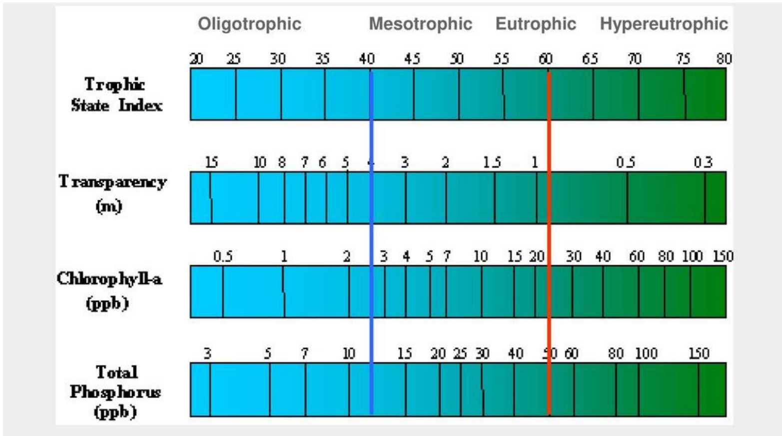

Figure 3: Graphic showing the various trophic states based upon the total phosphorus, chlorophyll-a and Secchi depth (transparency)

The trophic state index (TSI) uses total phosphorus, chlorophyll-a, and Secchi depth to define the trophic state (oligotrophic, mesotrophic, and eutrophic) of a lake (Carlson and Havens, 2005). The index is designed so that the same numerical trophic index will result based on correlations between phosphorus concentration, chlorophyll concentration, and Secchi depth. Since the TSI for these three parameters was nearly the same when reviewing historical data sets, it was likely that the phosphorus was limiting algae growth, and the low phosphorus is the major contributor to water clarity in Lake Owen (Carlson and Havens, 2005). Since total phosphorus is strongly correlated with chlorophyll production (a measure of algae growth) and algae growth is likely the main source of light attenuation in Lake Owen, comparing the TSI values for these parameters can indicate potential dynamics in the lake. Zooplankton in the lake will graze on algae, which can reduce light attenuation and increase water clarity. If zooplankton grazing is a significant source of water clarity, it would be expected that the phosphorus TSI would be higher than the chlorophyll and Secchi depth TSI (Carlson and Havens, 2005). This is because the phosphorus would be high enough to expect more chlorophyll production and therefore less clarity. The observations were higher water clarity in 2013-14 not lower water clarity, which would contradict this expectation. Furthermore, most soluble reactive phosphorus (SRP) data during the 2013-14 analysis were undetectable, indicating SRP was being used up.

In stratified lakes, the lake is separated by the warm water on the surface (the epilimnion) and cold water near the bottom (the hypolimnion). With the colder water being denser, the lake generally only mixes in the epilimnion, with the hypolimnion water remaining stagnant near the bottom. Diffusion of nutrients would generally occur at the metalimnion (transitional layer between epilimnion and hypolimnion). Often times, lakes will become anoxic in the bottom sediments, resulting in the release of phosphorus from the sediment (internal loading) due to the reduction of iron. In lakes that are strongly stratified, the hypolimnetic water (bottom layer) cannot reach the epilimnion, making the phosphorus that has built up unavailable to the epilimnion. In lakes where mixing can occur deeper (causing a flux from the hypolimnion layer) phosphorus can increase in the epilimnion layer and mix, leading to more productivity, and decreased water clarity (Cantin et al, 2011).

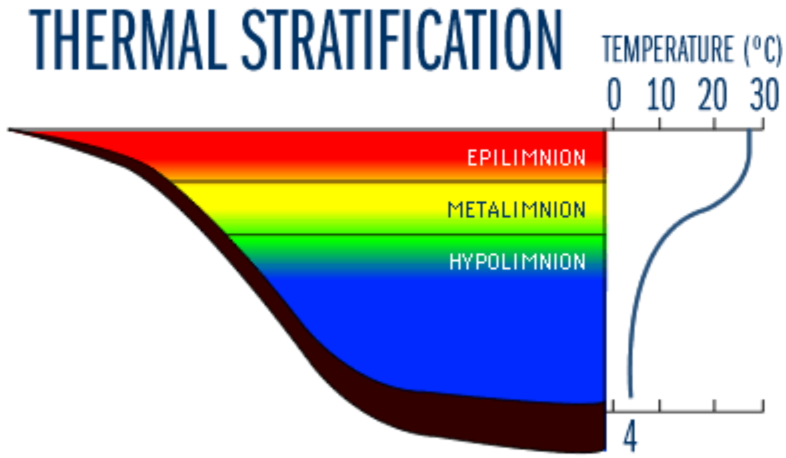

Figure 4: Layers during stratification of a lake.

Stratification is the layering of the lake based upon water density. There are three layers:

Epilimnion=top, less dense layer that more readily mixes.

Metalimnion=middle layer where the temperature decreases and density increases dramatically.

Hypolimnion=deep layer of dense water which remains stable and doesn't reach upper depths until turnover occurs.

Strong stratification can create a stable lake water column, reducing mixing from winds. The stability of the lake can be expressed using Schmidt's Stability Index, which indicates the work required to destabilize the lake (Adams and Charles, 2001). The higher the Schmidt's Stability, the more work (wind or heat currents) needed to mix the lake. Another calculation, referred to as the Wedderburn number, indicates the probability of a wind of a certain velocity creating enough shear that the lake will mix rather than remain stratified. A Wedderburn number greater than 1 indicates the lake will not likely mix, and <1 more likely to mix (Adams and Charles, 2001).

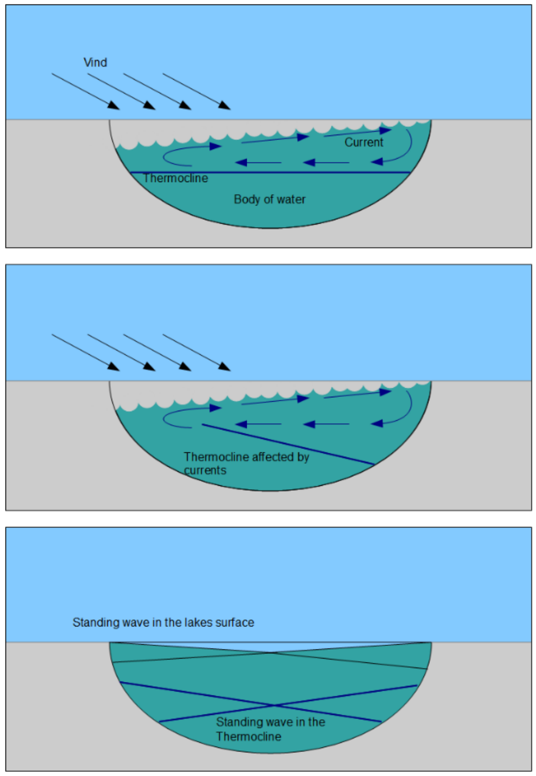

Figure 5: Graphic showing the effect of wind on the mixing of the lake through seiche formation. Graphic by Frankemann - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=30791432

Algae production is limited by nutrients and light. In most Wisconsin lakes, the nutrient that limits productivity is phosphorus (Shaw et al, 2004). Lake Owen is phosphorus-limited. This means that if phosphorus amounts are low, algae growth is limited and will increase significantly with small increases in phosphorus. Since photosynthesis is driven by light, limited light penetration will result in limited photosynthesis, thus limited algae production. For algae production to be maximized, an adequate amount of phosphorus must be available along with enough light intensity. Algae production can be measured as a concentration of chlorophyll (chlorophyll-a). The light intensity can be measured as PAR (photosynthetic active radiation), which are the photons of light that will drive photosynthesis. Typically, the euphotic zone of the lake (depth at which there is enough light to grow plants/algae) is defined as 1% of the lake surface PAR reading (Tilzer, 1987).

In the 2015 Lake Owen Comprehensive Management Plan, there was a discussion regarding a high concentration of phosphorus in the hypolimnion. It was also established that the Lake Owen was strongly stratified and any phosphorus that was reaching the epilimnion was through limited diffusion, thus limiting algae production to the metalimnion. The data set used in the management plan was limited to phosphorus and chlorophyll-a sampled near the surface and phosphorus in the hypolimnion, with limited data in the metalimnion (no chlorophyll-a was sampled in metalimnion). In the dissolved oxygen profiles, the oxygen was consistently higher in the metalimnion (as compared to epilimnion) which was used to conclude that there is a higher concentration of algae in this zone than in the epilimnion.

The nutrient that limits algae production in Lake Owen is phosphorus (Lake Owen Comprehensive Management Plan, 2015). Two forms of phosphorus are measured to analyze the trophic states of lakes: soluble reactive phosphorus (SRP) and total phosphorus (TP). SRP is bioavailable, meaning this is the form organisms can absorb and utilize. TP includes SRP, as well as other forms of phosphorus. TP has a strong correlation to chlorophyll-a production, higher TP concentrations lead to higher chlorophyll-a concentrations. SRP is typically low, largely because algae and/or plants absorb it faster than it is replenished. If the SRP is not decreasing (or it is increasing) during algae productivity, it is being supplied faster than absorbed or it is being recycled by zooplankton. As zooplankton consume algae, the chlorophyll-a production is lowered, leading to less SRP absorption from the primary producers (algae) (Carlson and Havens, 2005)

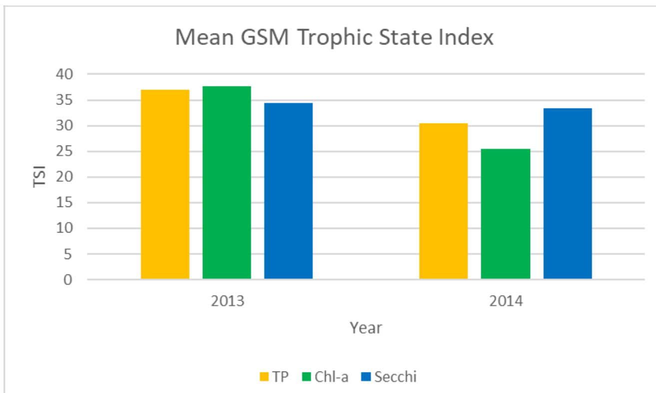

Figure 6: Graph comparing TSI values for TP, chlorophyll-a and Secchi. Note the similar TSI values between TP and chlorophyll or Secchi depth and in the case of 2014, the Secchi depth TSI was higher (less clear) than the phosphorus or chlorophyll TSI values.

The goal of this evaluation is to focus on the interaction between the epilimnion and hypolimnion (at the metalimnion) and determine if chemical and morphological characteristics in Lake Owen are dictating water clarity, before analyzing the food web. Since historical data shows low epilimnion phosphorus and chlorophyll-a concentrations, as well as significant stratification throughout the growing season, this analysis evaluates the interaction of these vertical zones.

Methods

The focus of the study was on the epilimnion and metalimnion dynamics in relationship to nutrients and chlorophyll. Historical data collection sites were used, with most of the data obtained from the north basin deep hole. The North Basin Deep Hole is a moderately deep basin in fairly close proximity to the outlet of Lake Owen. Figure 7 shows the location of the data collection sites.

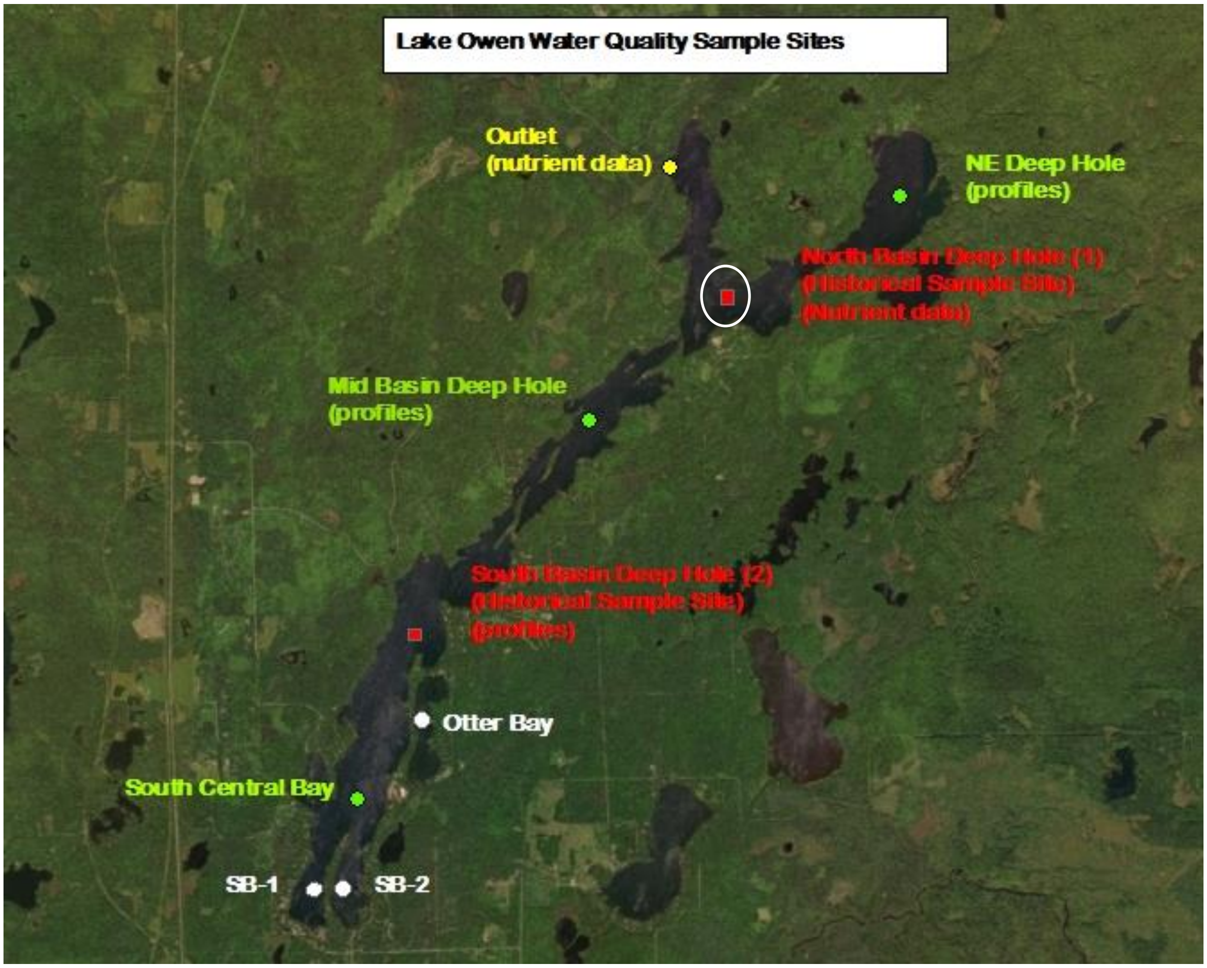

Figure 7: Basin locations/data collection locations in Lake Owen.

Chemical data collection

Over the time period June-Oct. 2019, the DO, temperature and specific conductance were measured every meter from the surface to bottom using a YSI Pro 2030 meter. Soluble reactive phosphorus (SRP)[1], and chlorophyll-a were collected twice per month. Phosphorus was collected at 0-2 meters (integrated), and 4-9 meters at one-meter intervals twice monthly and at 14 meters approximately once per month. Chlorophyll-a was collected at 0-2 meters, and 4-9 meters twice per month. All water samples were analyzed at the Wisconsin State Lab of Hygiene. A Van Dorn water sampler was used to collect discrete water samples at the various depths discussed. An integrated sampler that samples in the top 2 meters was utilized for the integrated samples. The water was transferred directly to sample bottles packed in ice and shipped. The TP samples were acidified with sulfuric acid.

The SRP was the nutrient species that was the focus since SRP is the bioavailable phosphorus to be used by plants and algae. The SRP is typically low, largely because it is absorbed by algae (Bradford and

[1] Total phosphorus collection was suspended after July when it determined that the WI State Lab of Hygiene tests were not sensitive enough to accurately determine Lake Owen TP levels.

Peters, 1987). The SRP is included in the TP concentrations, which include all other forms of phosphorus as well. Due to the correlation between TP and chlorophyll, TP samples were also taken initially. However, some of the data results showed TP values at lower concentrations than the SRP, which does not make chemical sense. The LOQ (Limit of Quantification which is the lowest value that can represent the concentration of that analyte) for TP at the State Lab of Hygiene is 27 ug/L. All TP values were far below this level, and there was not an alternative method to lower the LOQ. However, the LOQ for SRP is 7 ug/L, so those results were more accurate since most of these values were above 7ug/L. As a result, the TP sample collection was ended in the nutrient profiles but retained at the outlet and at fall turnover.

Tropic state index (TSI) was used to compare total phosphorus concentrations (with SRP as a surrogate), chlorophyll-a concentrations, and Secchi depths. The calculated TSI showed trophic state relationships. The Carlson Trophic Index is for total phosphorus and is technically not to be used for SRP. However, since SRP is included in the TP, using SRP to calculate TSI for phosphorus would represent a minimum TSI for phosphorus, understanding TP values would increase this value to some degree.

Other secluded bays

Chemical and physical profile data were also collected at Otter Bay, the South Basin Deep Hole and SB-1 to evaluate the nutrient and chlorophyll differences throughout the lake, as well as determine the degree of stratification (except in Otter Bay). Phosphorus and chlorophyll-a were collected as a 0-2 meters integrated sample and the DO/temperature/specific conductance profiles were collected from surface to bottom in one-meter intervals.

Strength of stratification

There were three values calculated to evaluate any potential mixing in the lake: stratification index, Schmidt's Stability Index, and the Wedderburn number. In addition, the mean monthly thermocline depth, top border of the metalimnion, and bottom border of metalimnion were determined at the North Basin Deep Hole. The Lake Analyzer tool for R studio was used to determine these depths at various intervals throughout the summer growing season. The stability of the lake was assessed by calculating the Schmidt's Stability Index and the Wedderburn number using the Lake Analyzer tool in R (Winslow et al, 2019). The stratification index was calculated by determining the standard deviation (SD) of the density of the water at the temperature at each depth X 1000 (SI = (SD of density at each depth) X 1000).

Zooplankton enumeration

To determine possible response to nutrient and chlorophyll changes, zooplankton were enumerated. The total number of rotifers, copepods, and cladocerans per L of water were measured. A Van Dorn water sampler was used to sample water at 2-10 meters in 2-meter increments. A 250 ml subsample was collected from the water sample and preserved with Lugol's solution (James, 1991). The sample was placed into a settling cylinder for 24 hours to allow for plankton to settle. The sample was reduced to approximately 50 ml checking each water volume removed for zooplankton. The remaining 50 ml sample was transferred in approximately 10ml aliquots to a Ward counting wheel until all of the samples were analyzed (James, 1991).

Light intensity

To evaluate light limiting conditions, the Secchi disk depth was measured weekly. A PAR reading was measured from the surface to 10 meters (and at Secchi depth) to evaluate the light available for photosynthesis using a PAR sensor mounted to the edge of the Sechhi disk.

Results:

The results breakdown is separated by data collection type.

Water clarity, strength of stratification and thermocline determination

The water clarity in Lake Owen at the North Basin Deep Hole study site is shown to be excellent by the Secchi disk depths. The Secchi disk depth ranged from 9 meters on June 10, to 5.5 meters in October. The mean Secchi disk depth over the growing season was 6.92 meters. The Carlson Trophic Index for the Secchi depth means is 32, which is oligotrophic.

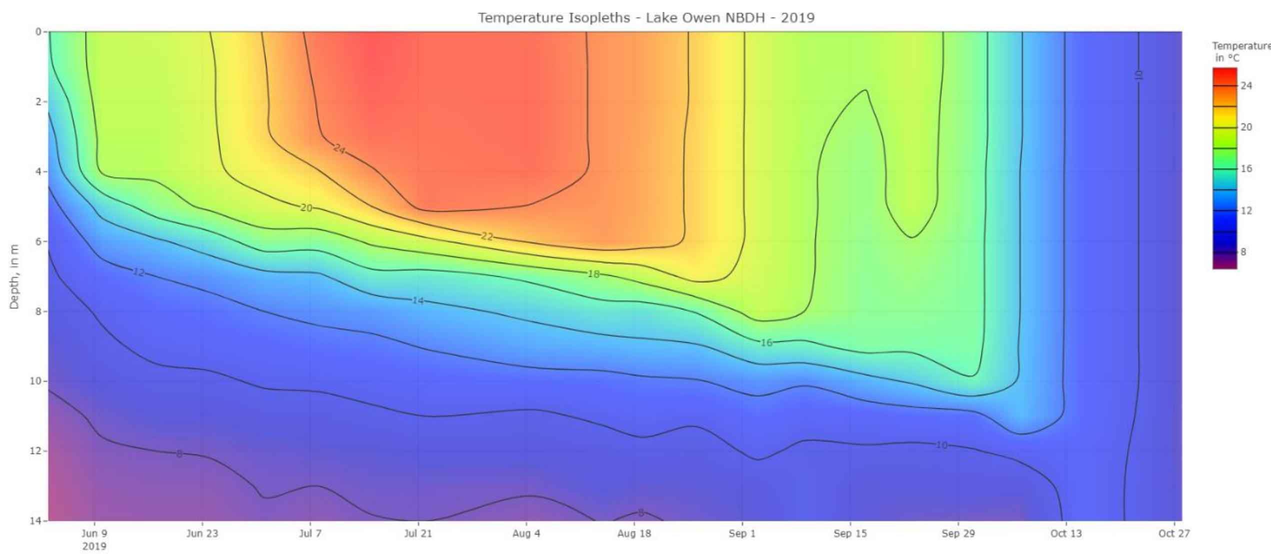

Figure 8: Temperature profile of north basin deep hole from June-Oct. This profile shows the strong stratification with a distinct “barrier” between the hypolimnion (dark blue/purple) and epilimnion (red/yellow).

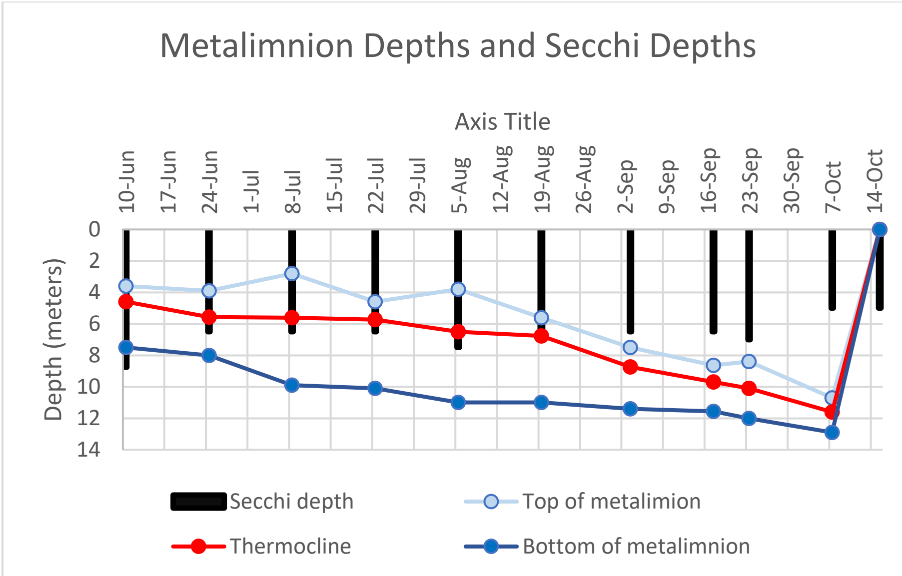

Figure 9: North Basin Deep Hole Metalimnion, thermocline depths and Secchi depths bi-weekly. The metalimnion deepens as the summer progresses. The deepens the mixing layer (epilimnion).

The thermocline was shallower in June than the rest of the growing season, starting at about 4.5 meters. The top portion of the metalimnion was just under 4 meters and the bottom nearly 8 meters in June. As the growing season progressed the thermocline depth continually became deeper, reaching a maximum of 12.5 meters on October 7. By this time the metalimnion began to decay and the lake started to mix due to fall overturn. From mid-June until mid-August the Secchi depth is nearly the same depth as the thermocline. After mid-August, the thermocline and metalimnion were deeper than the Secchi disk. By mid-September, the metalimnion began to narrow and decay, leading to mixing.

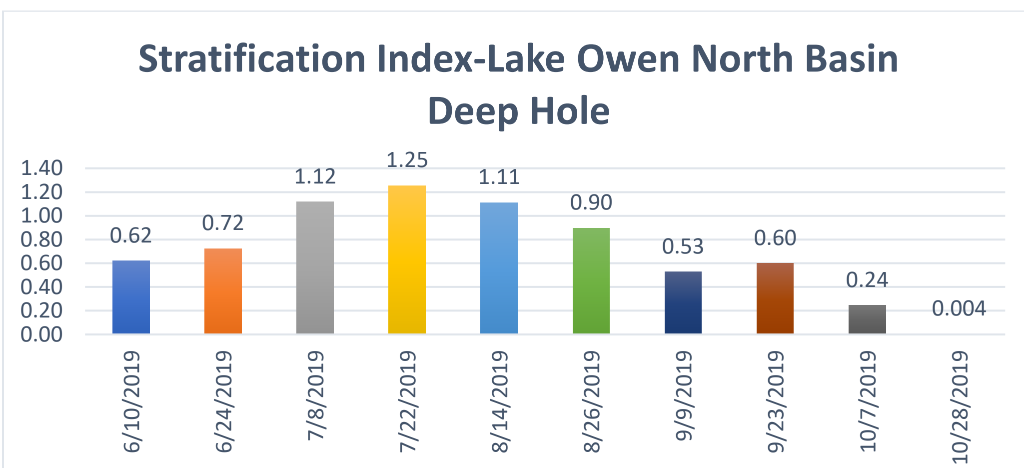

Figure 10: Bi-monthly stratification index in North Basin where chemical data was collected.

The temperature profile data were used to determine the degree of stratification in the basin. As figure 10 shows, the stratification index continued to rise from June until mid-July. The index slowly decreased until Oct. 28 when it was near zero. The higher the stratification index, the stronger the stratification. Any value above 0.2 is considered stratified.

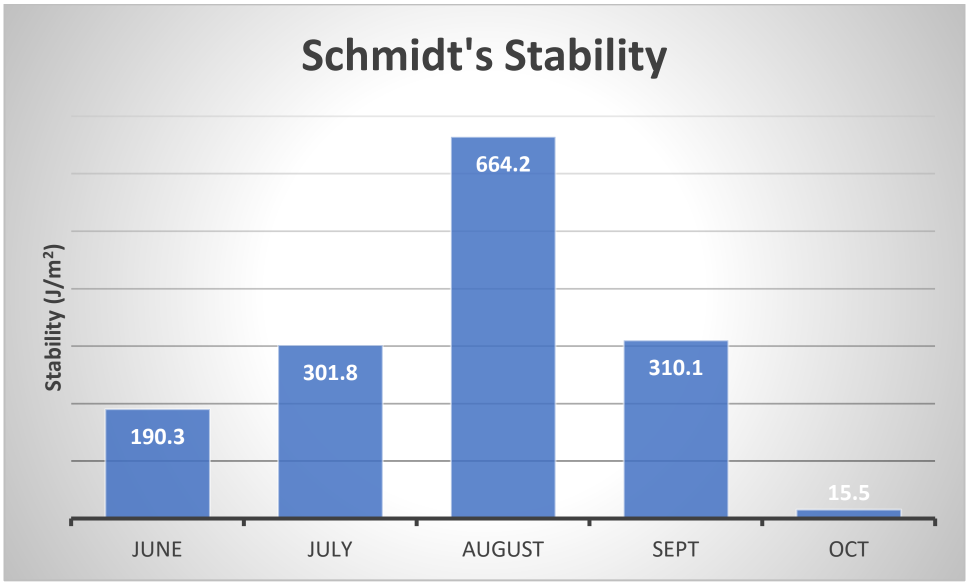

Figure 11: Monthly Schmidt's stability values for Lake Owen, 2019. The lake is very stable from June until mid-October.

The profile data was also used to calculate Schmidt's stability The higher the value the more work it takes to mix the lake. Similar to the stratification index, the Schmidt's stability increased starting in June to a maximum in August and fell to a low value in October, when the basin eventually mixed. Both of these graphics show that this basin likely did not mix from June until late October.

As the bathymetry (depth) map shows, Lake Owen is narrow, with depth changing very quickly from shallow near shore to deep. Even though the lake is long, the fetch of the lake is not long, with the lake being secluded by heavy forest. These morphological characteristics lead to a stable stratification, which results in no mixing between the hypolimnion and the epilimnion during the growing season.

Chlorophyll-a, dissolved oxygen and PAR

Chlorophyll-a represents the production of algae. Since Lake Owen has such a high-water clarity, color is not considered an issue in water clarity. Therefore, the production of algae likely determines water clarity (more growth results in lower water clarity).

The chlorophyll-a in the epilimnion was highest in May and declined somewhat each month. Another observation is that the chlorophyll-a concentration was highest (except for one data collection period) at depths within the metalimnion. Figure 12 shows the monthly means for chlorophyll-a from the near surface (0-2 meter depth) to 9 meters (depths of 4-9 meters).

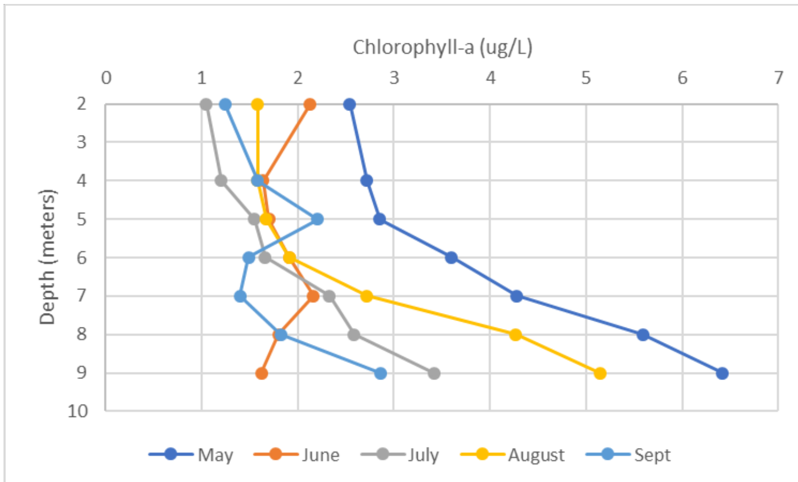

Figure 12: Chlorophyll-a profile (monthly averages) in North Basin.

Figure 13 shows the growing season means of chlorophyll-a at each depth. The graph reflects the consistent trend of chlorophyll increasing at depths near and within the metalimnion. The Carlson's Trophic Index for chlorophyll was 34-37 depths down to 6 meters. It increased to 41-43 at 7-9 meters in the metalimnion, which is just into the mesotrophic level.

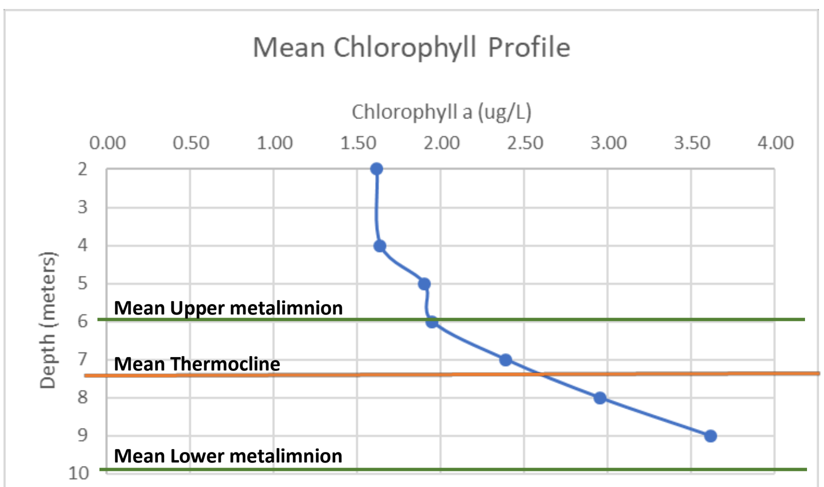

Figure 13: Mean chlorophyll-a profile in North Basin with mean thermocline depth for reference.

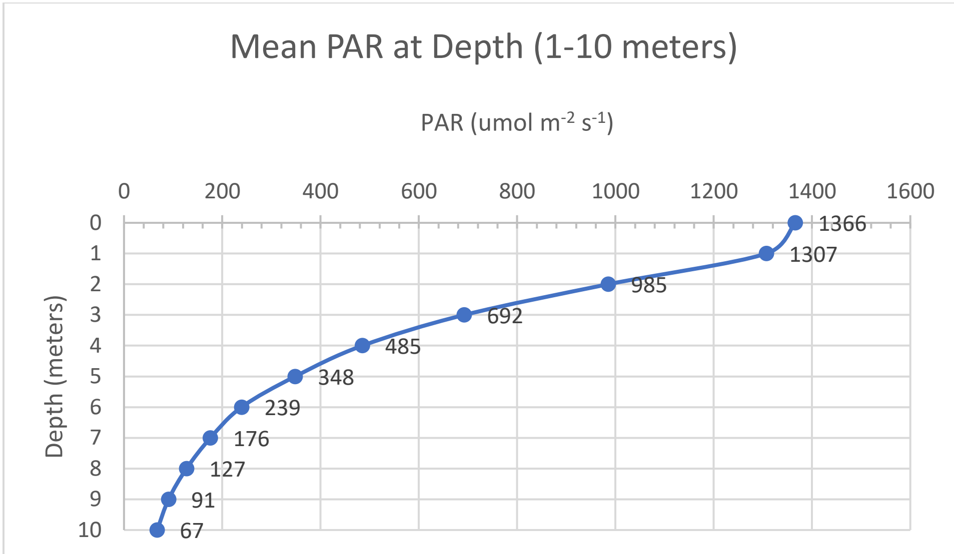

Figure 14: Mean PAR at discrete depths from surface to 10 meters. At 10 meters it is 4.9% pf the surface PAR reading.

The PAR readings were taken each week over the growing season, and Figure 14 shows the mean of the PAR values from 1 meter to 10 meters of depth. The euphotic zone (where light is intense enough for photosynthesis) has been defined by literature as 1% of surface PAR. The mean PAR reading at 10 meters is 67, which shows the euphotic zone extending beyond 10 meters since it is above the 1% threshold (13.7 would be 1% of surface). This would indicate that photosynthesis, thus algae productivity, is not limited by light down to 10 meters in Lake Owen.

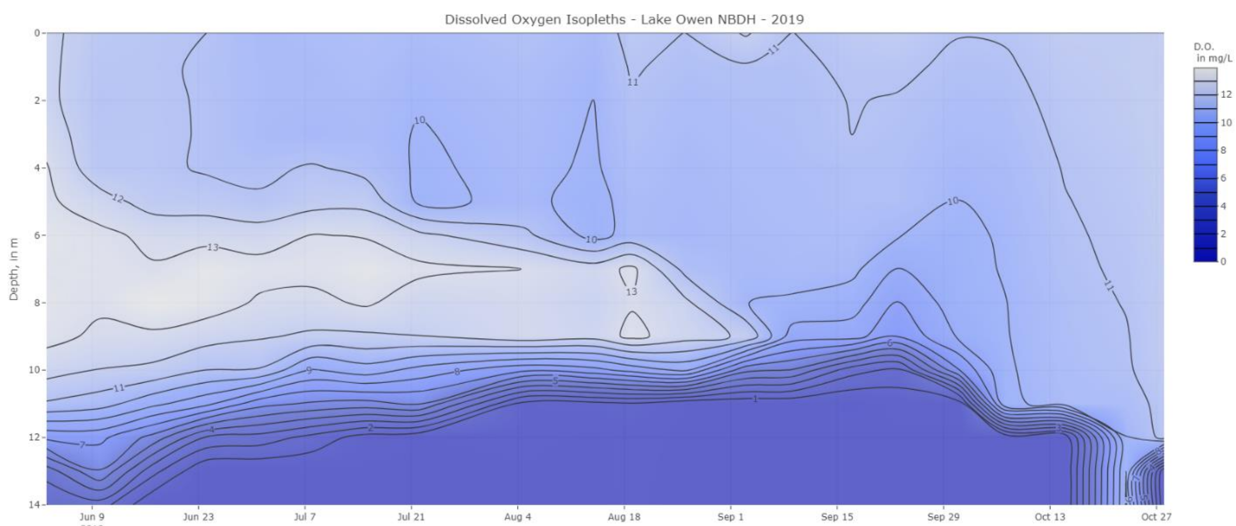

Figure 15: Dissolved oxygen profile at north basin deep hole, 2019 from May until Oct. Note the high oxygen conditions from June through early Sept between 6 and 8 meters. This is consistent with higher chlorophyll (thus algae growth) in the metalimnion.

The dissolved oxygen profile (Figure 15) demonstrates strong stratification with a steep decline in dissolved oxygen below the metalimnion. It also shows turnover in late October with no full mixing of the entire water column. Lastly, there is higher dissolved oxygen in the metalimnion, which further supports more algae present in the metalimnion from June through early September.

Soluble reactive phosphorus (SRP)

The form of phosphorus that is available for use by algae is soluble reactive phosphorus. The concentration of SRP was measured every two weeks from the near surface (0-2-meter integrated sample) down to 9 meters, which is at or just below the metalimnion over most of the growing season. Figure 15 shows the monthly means for each depth measured.

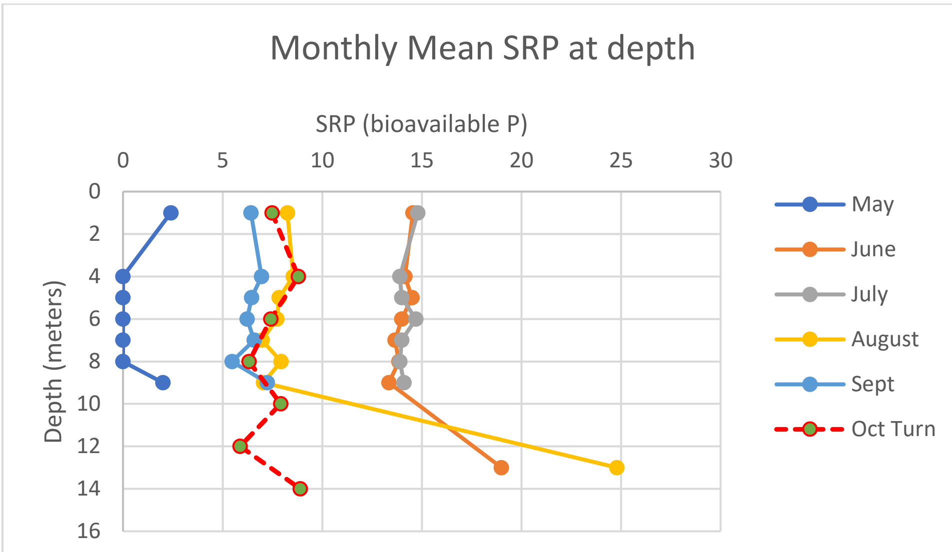

Figure 16: Soluble reactive phosphorus profile in North Basin (monthly averages). The June and July Concentrations are higher then fall turnover as well as all other months.

As the graph shows, the SRP was lowest in May and the highest in June and July. One might expect higher phosphorus values earlier in the growing season from spring runoff events and from mixing during spring overturn. There are no indications of destratification of the lake in June or July, so the source of this phosphorus would likely be external sources. Further, the fall SRP levels in the metalimnion which are lower than the June and July values, indicate the phosphorus did not come from the lower lake layers. That external source of phosphorus is unknown. After July, the SRP decreased over the remaining growing season. This is likely due to the increased depth of the thermocline, reducing any mobilization of phosphorus to the epilimnion. Reduced SRP could also be due to absorption by algae, although the Secchi depth suggests less algae.

Another trend was for the SRP to be higher in June and July in the epilimnion. Some occasional SRP samples were collected at 13 meters to verify even higher SRP in the hypolimnion. As the graph displays, the SRP was highest at 13 meters. The SRP in the metalimnion could be the result of algae absorbing bioavailable phosphorus, resulting if lower concentrations of SRP dissolved in the water.

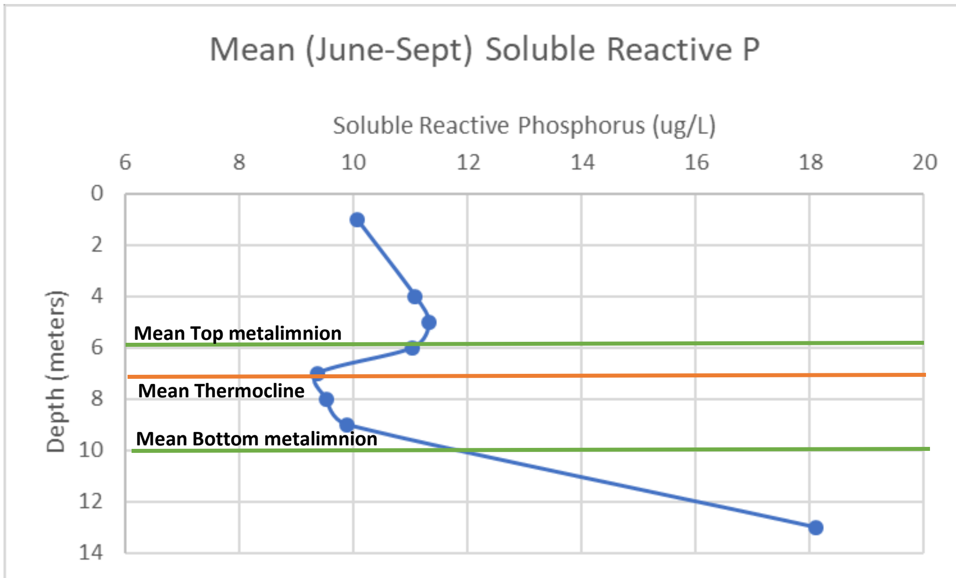

Figure 17: Mean SRP profile with metalimnion and thermocline depths for reference.

Figure 17 shows the mean SRP at each depth over the growing season. The various temperature-depth zones are included to see the relationship between the SRP and these zones. Interestingly, the SRP is lower in the metalimnion on average, with slightly higher levels in the epilimnion and much higher in the hypolimnion. The chlorophyll-a values were highest in the metalimnion over the growing season, and it may be that that lower SRP in the metalimnion is due to algae absorbing SRP.

The profiles do not demonstrate mixing between the hypolimnion and the epilimnion. This would indicate that most of the phosphorus in the epilimnion is not from hypolimnion. It appears that algae growth is limited by nutrients with highest algae productivity in the metalimnion, where there is generally more phosphorus available. The mean SRP would be lower in the epilimnion depths without the high June/July concentrations.

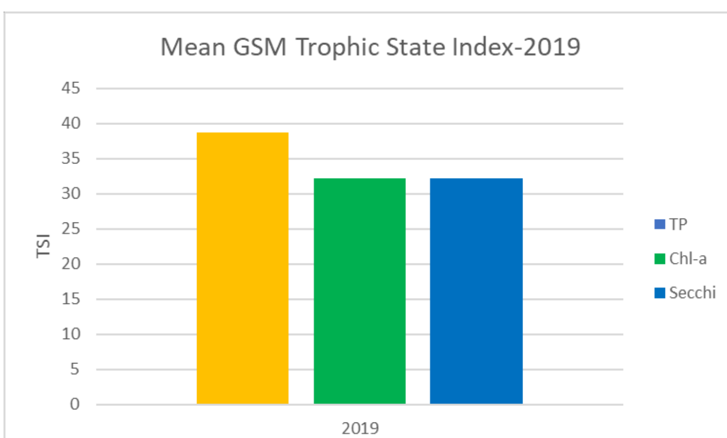

Figure 18: Comparison of epilimnion TSI values for TP, chlorophyll-a and Secchi 2019. Note the higher TSI for phosphorus than chlorophyll and Secchi TSI's, which are the same.

Since the TSI for phosphorus is higher than the chlorophyll and Secchi depth TSI's, the SRP value can be used to estimate the potential chlorophyll-a concentration from the phosphorus concentration, using a regression established by Havens and Nurnberg in 2004. Using their regression equation, the GSM mean for chlorophyll a could be 4.40 ug/L. This would give a TSI of 44.3. If the TSI values are simply made the same as phosphorus (estimated from SRP), the chlorophyll concentration would be 2.3 ug/L and the Secchi depth would be approximately 4.3 meters. The GSM in 2019 in the epilimnion for chlorophyll was 1.6 to 1.8 ug/L and the Secchi depth GSM was approximately 7 meters.

Zooplankton enumeration

Water samples were collected and a zooplankton were enumerated at depths ranging from 2 meters to 10 meters, in 2-meter intervals at the North Basin Deep Hole. The zooplankton were classified as rotifers, copepods, and cladocerans, counting the number in each category. Figure 18 shows the total zooplankton counts at each depth, June through September.

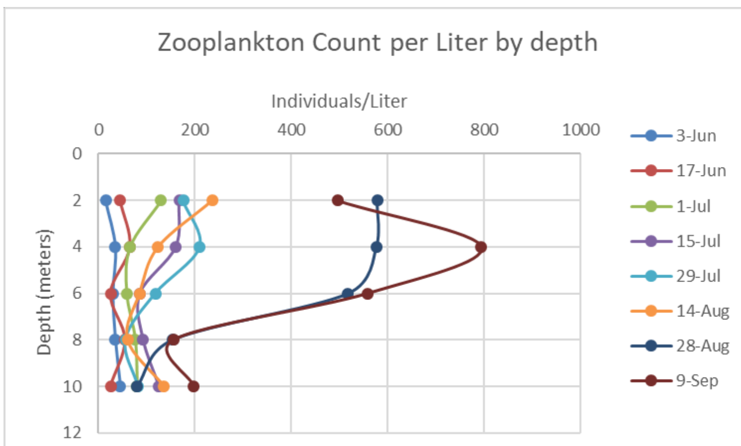

Figure 19: Zooplankton count (all categories) at 2-meter depth intervals to 10 meters. Note the slow increases, with a large spike in August and Sept.

As the graph demonstrates, the total zooplankton count increased over the course of the growing season, and a significant increase occurred in late-August and early September. The biggest increases occurred in the epilimnion (top 6 meters). This would suggest that there is increased productivity of algae as the water warms and the zooplankton forage on the algae. The main contributors to zooplankton numbers were rotifers, which are the smallest zooplankton categorized in this analysis. Rotifers eat very small algae and can also be used to indicate productivity in the limnetic zone. Interestingly, the highest chlorophyll concentrations were in the metalimnion, indicating the highest algae productivity, yet there were fewer zooplankton of all types found in the metalimnion compared to the epilimnion in late-August and early September. Cladocerans, which are more mobile and much larger than rotifers, were found somewhat more frequently in the metalimnion compared to the epilimnion in most sample periods. See Figure 19 for that count evaluation.

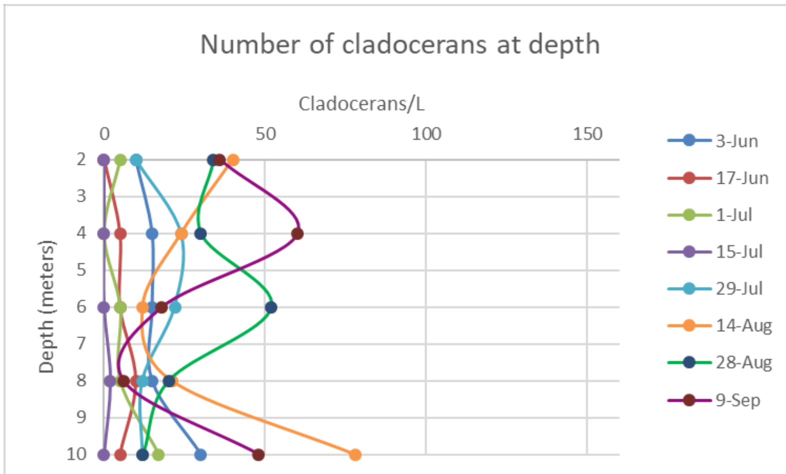

Figure 20: Cladoceran counts at 2-meter intervals to 10 meters.

Other Basins Chemical Data

Soluble reactive phosphorus and chlorophyll-a concentration were collected in two secluded bays to evaluate the influence of development around the bays on water quality. Samples were also taken in the south basin deep hole to compare between the bays and the north basin.

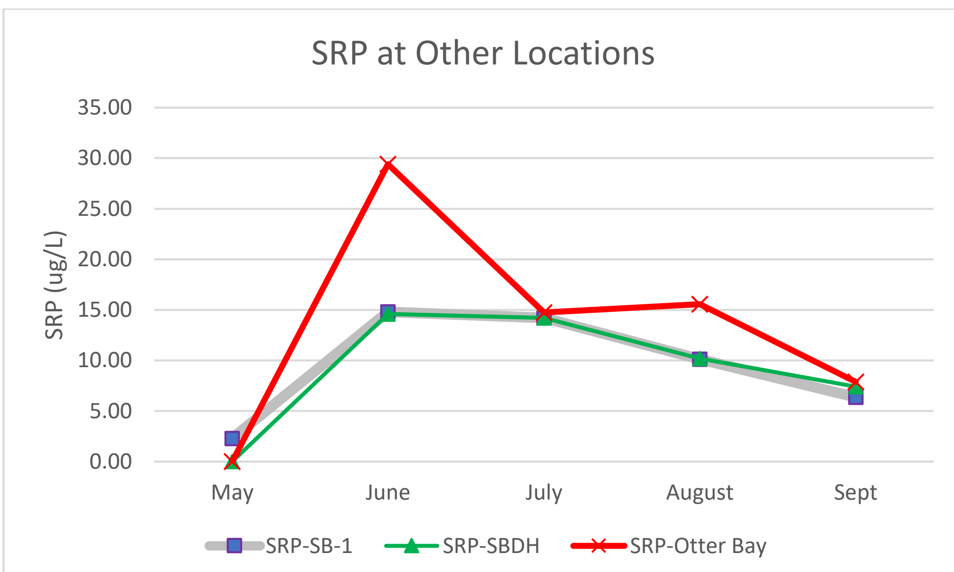

Figure 21: Mean monthly SRP concentrations in secluded bays and the south basin.

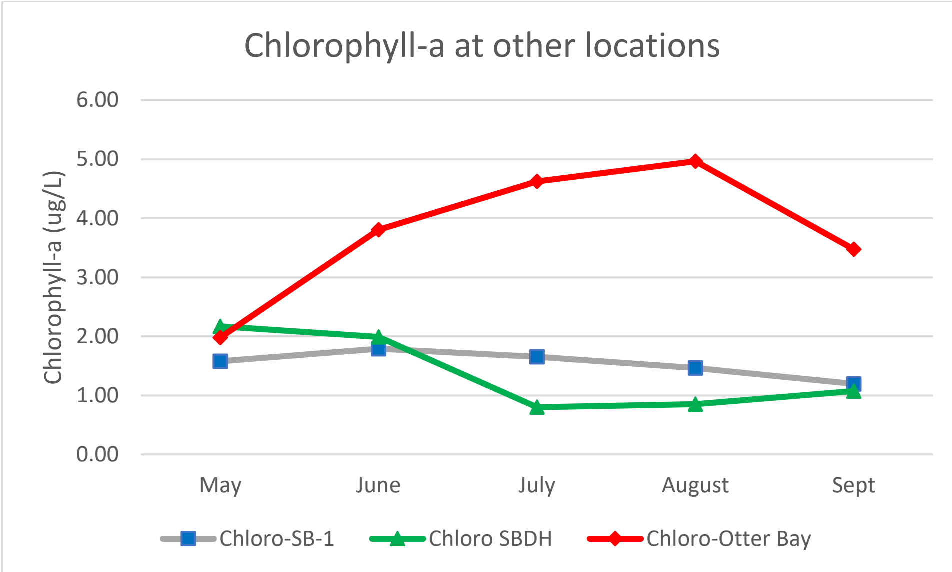

Figure 22: Mean monthly chlorophyll-a concentrations in secluded bays and south basin.

The southern secluded bay (SB-1) had nearly identical values to the south basin deep hole. All chlorophyll values had oligotrophic TSI, but the phosphorus TSI was in the mesotrophic range June-August. However, Otter Bay had values much higher in phosphorus in June and August, and much higher chlorophyll concentrations in all months June-Sept. In June the phosphorus TSI was eutrophic and all other TSI values were mesotrophic in Otter Bay.

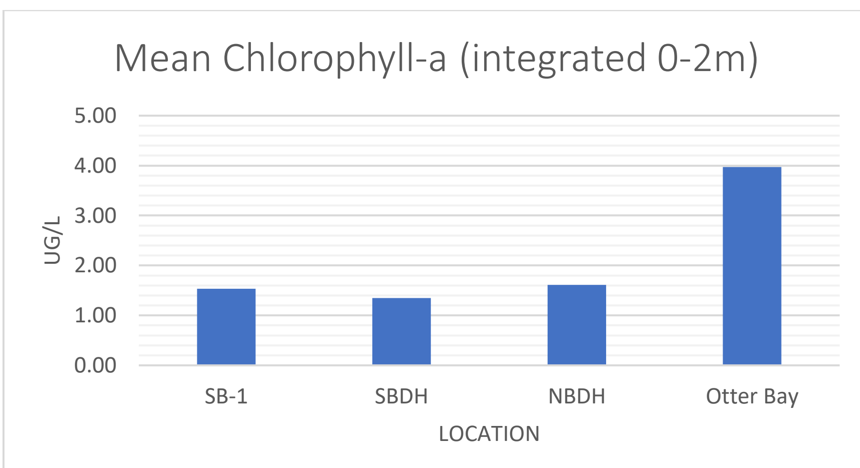

Figure 23: Mean chlorophyll-a data (integrated samples) from all basins May-Sept. All basins are similar except for Otter Bay, which is much higher.

Discussion

The phosphorus, chlorophyll and Secchi depth data from 2013-14 supported the hypothesis that phosphorus limits algae growth and the high clarity is due to low phosphorus levels. The TSI values of all three data were similar, suggesting that the phosphorus was limiting the production of algae. In 2013-14, most samples had SRP below detectable levels, which indicated that the algae absorbed phosphorus, creating an even lower concentration of bioavailable phosphorus remaining than expected. Most of the algae productivity appeared to be at or near the metalimnion (based on increased dissolved oxygen values not actual chlorophyll values), demonstrating phosphorus limited production in the epilimnion and the algae were growing where there was more phosphorus in the metalimnion. However, if zooplankton were grazing significantly on algae, the TSI for total phosphorus would be higher than the TSI for chlorophyll and Secchi depth (it is possible that the LOQ of total phosphorus could cause this difference, but the testing utilized is unknown).

In 2019, the data set was more comprehensive than in previous data sets, focusing on more samples just above, within, and just below the metalimnion. The profile data in the north basin deep hole indicated that the lake was strongly stratified from early in the summer, until the end of October. This stratification likely reduced the flux of phosphorus from the hypolimnion (where there is a pool of higher concentration phosphorus). This would mean that most of the phosphorus in the epilimnion was from runoff and aerial loading from precipitation and atmospheric deposition.

The highest chlorophyll readings in the epilimnion were in late May. This corresponded with the lowest SRP values in the epilimnion. This shows that the lake likely received a phosphorus load in the spring melt and turnover which resulted in algae production, and absorbed the SRP in the epilimnion. The chlorophyll concentrations in the epilimnion decreased each month during the remaining growing season. This was coupled with an increase in zooplankton numbers. During June, there was an increase in SRP in the epilimnion. The metalimnion was shallower in June than in July and later, but there is no evidence to suggest there was any mixing between the metalimnion and the epilimnion. The shallower the metalimnion, the more wind and currents can contribute to mixing. The metalimnion was most shallow early in the growing season. It is possible that some diffusion occurred, but the main source of SRP was likely external in June and July. It is possible that pine pollen was the source.

Early in June, the pollen release into Lake Owen was observed and was dense in the air and on the water. We do not know for certain if pollen was the source of increased phosphorus in June, but no major precipitation events or mixing events can account for it. Loads as high as 11.2 mg/m^2 from conifer pollen in May/June have been observed in Ontario Lakes (Banks and Nighswander). At 11.2 mg/m^2, the potential phosphorus load into Lake Owen is 57-58 kg. The increase in phosphorus in the epilimnion from May to June was estimated to be 68 kg. Therefore, it is plausible pollen increased phosphorus in the epilimnion in June. There was a significant precipitation event on June 30 (1.86 inches) that could also have fluxed phosphorus into the epilimnion, maintaining phosphorus into July.

The mean chlorophyll profile, SRP profile and the PAR profile show that algae productivity is likely not light-limited and is likely nutrient-limited. The PAR profile shows that the light intensity decreases substantially with depth, but is still high enough at the metalimnion all summer for photosynthesis. Furthermore, the chlorophyll concentration is higher on average in the metalimnion compared to the epilimnion. Lastly, the SRP is lowest (on average) in the metalimnion, which is likely due to the uptake of SRP by the higher algae population. This is further supported by higher DO values in the metalimnion all weeks measured, since algae produce oxygen when they undergo photosynthesis.

Since Lake Owen has such clear water in the epilimnion, it is also plausible that UV radiation is limiting algae growth. Although solar radiation from sunlight is a key component to photosynthesis and algae growth, it can also be detrimental. A study has shown that limitations of phosphorus and UV radiation has a more profound effect on algae production than photosynthetically active radiation (PAR). As phosphorus increased and UV radiation decreased, algae production increased in one study (Xenopoulos et al 2002). This could be another factor in more algae being present in the metalimnion of Lake Owen.

In comparing the TSI values for phosphorus, chlorophyll and Secchi depth, there is evidence that zooplankton are grazing on algae, resulting in increased water clarity. The TSI for phosphorus is estimated in the mesotrophic range (no reliable TP value, but the TP would be higher than the SRP, so using the SRP gives minimum value for TSI-TP). The chlorophyll and Secchi depths are similar with TSI values in the oligotrophic range. It is predicted in this situation that zooplankton grazing is occurring to contribute to water clarity (Carlson and Havens, 2005). The zooplankton counts did increase each month from June to September. The August and September counts were significantly higher than in previous months. This compliments the monthly reduction in chlorophyll concentration each month, showing the increased zooplankton correlates with decreased algae (as shown through chlorophyll concentration), limiting phosphorus absorption. The predicted chlorophyll concentrations and Secchi depth from available phosphorus show that the water clarity would be worse without reduction in algae from zooplankton.

The grazing of zooplankton is not the only contributing factor in water clarity. Historical data supports reduced productivity from limited phosphorus. In 2019, data showed higher phosphorus values than previous years, and thus indicated zooplankton grazing reduced algae and increased Secchi depth. This shows that on any given year, the combination of limited nutrients and the response of zooplankton if a flux of phosphorus occurs, results in high water clarity (high Secchi depth readings) in Lake Owen. Some nutrient flux is good in Lake Owen as there is a need for productivity in the limnetic zone to support diverse populations in this ecosystem, including fish.

Two secluded bays were evaluated to determine if development around these bays would affect the water quality in regard to nutrients and chlorophyll. The southernmost bay (SB-1) had low chlorophyll values all summer, similar to the south basin deep hole. The epilimnion can mix in this area, especially horizontally, so any loading that may occur from the heavier development in this bay is likely mixed in the epilimnion and phosphorus and chlorophyll concentrations are diluted to match the rest of the lake. In Otter Bay the SRP and chlorophyll values were quite different from the rest of the lake. The SRP in June averaged 29 ug/L. This alone would put Otter Bay in the eutrophic range (TSI). The mean chlorophyll in Otter Bay was the highest in August, reaching 4.97. This is a TSI value of 46.3, which is mesotrophic.

In summary, the 2019 data set suggests little or no mixing of the hypolimnion into the epilimnion. The metalimnion had the highest mean chlorophyll readings and lower mean SRP values than the epilimnion. This shows that more algae were growing in the metalimnion where more phosphorus can be absorbed. There is evidence that there is surplus SRP available in the epilimnion in June and July from external loading. It appears that with increased numbers of zooplankton as the summer progressed, these zooplankton grazed on algae, reducing the SRP that got absorbed. This grazing was not supported in the 2013-14 data set, but is supported in 2019. Furthermore, since there is no indication of mixing (therefore no internal loading of phosphorus from the hypolimnion), there are external sources of SRP that will need to be evaluated.

It was determined from the 2019 data that Otter Bay is more susceptible to watershed flux of phosphorus. The concentrations of SRP and chlorophyll were higher than the rest of Lake Owen, both giving TSI values well into the mesotrophic state (phosphorus in eutrophic range one month).

Management implications

Since Lake Owen stratifies so strongly, it will take dramatic climate changes to increase the chance of mixing, where high phosphorus from the hypolimnion could be brought to the surface. The Wedderburn number in Lake Owen during July was 42.6 with a 10-mph wind, based upon the stratification of the lake at that time. Even with much higher winds, Lake Owen is not likely to mix during the growing season. The Wedderburn number was calculated for a 40-mph wind at 2m above the lake surface and was 0.81, indicating no mixing likely. The Wedderburn number needs to below 0.5 to indicate any likely mixing (Adams and Charles, 2001). Using a 50-mph wind the Wedderburn number is 0.51. Significant warming and/or precipitation could increase the depth of the thermocline, increasing mixing potential, but this would require significant changes.

The sampling in 2019 showed more SRP in the epilimnion than in previous data years. The source of this phosphorus is not known for certain but is external. The runoff from two significant rainfalls likely contributed some (one large rain event occurred June 30, 2019). Based on the timing of the June/July SRP increase, it is possible pollen from conifer trees was also a major source. Significant phosphorus loads from conifer tree pollen in lakes are well documented (Banks and Nighswander). The amount of pollen observed in the air and in the water in June was significant. Regardless, phosphorus should continue to be monitored annually at least in the north and south basins.

Since no mixing seems to occur during the growing season between the stratified lake layers, the phosphorus that fluxes directly into the epilimnion is important. The epilimnion has a much smaller volume of water compared to the entire lake depths. Therefore, land use within the watershed could have significant effects on the growth of algae. For example, if forested areas are converted to developed areas with impervious surfaces, the runoff will increase, bringing more phosphorus into Lake Owen.

Zooplankton is grazing on algae and seems to respond to the small increases in phosphorus leading to clearer water. The most likely change that could occur in the zooplankton community would be a change in the fish assemblage. However, this is unlikely unless there was a major decrease in all predatory fish, resulting in an increase in small baitfish. Baitfish are most likely to consume zooplankton. Also, the dominating zooplankton were rotifers, which are consumed by very small fish.

The data suggests Lake Owen has a healthy dynamic of limited nutrients providing enough productivity to sustain balanced algae and zooplankton communities. Maintaining natural shorelines and watershed with low levels of nutrient runoff will help maintain this pristine lake ecosystem.

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Glossary of limnological terms

Anoxic-A state of having little oxygen (generally < 1 mg/L).

Aphotic zone-The portion of the lake where incident light level is less than 1%.

Bathymetry-The depth characteristics of a lake.

Biomass-The total weight of organisms per unit area at any given moment in time.

Chlorophyll-The green pigment in plants and algae that absorb light for photosynthesis. On of the two forms (chlorophyll-a) is used to represent the amount of phytoplankton (algae) in the water column.

Cladoceran-An Order of the Class Crustacea.

Copepoda (Copepod)-A subclass in the Class Crustacea.

Epilimnion-The warm oxygen rich, upper layer of a lake; less dense than lower layers.

Euphotic zone-The portion of the lake where photosynthesis can occur due to sufficient light.

Eutrophic-A classification of a lake meaning that the lake is highly enriched (with nutrients).

Fetch-The distance that wind can blow over water without interruption by land.

Growing season mean (GSM)-The months where growing of plants and algae will occur. Generally considered May through September.

Hypolimnion-A lower cold layer of a lake that lies below the metalimnion.

Limnetic zone-The open water zone of fresh waters (lake).

Littoral zone-The zone predominated by aquatic plants.

Macrophytes-Large aquatic plants.

Mesotrophic-Those lakes that are moderately enriched. Between oligotrophic and eutrophic.

Metalimnion-The intermediate layer in lakes between the epilimnion and the hypolimnion. The metalimnion is the zone of very rapid changes in temperature (>1^{o}C/meter).

Morphometry-The method of measure and analyzing the physical dimensions of a lake; a function of underwater contour lines, the shape of the lake, and its geologic origin when describing a lake.

Oligotrophic-A trophic classification of lakes having little nutrients.

Photosynthetically active radiation (PAR)-The light that is useable by most aquatic plants/algae.

Phytoplankton-The plant members of plankton community which are suspended or free-floating in the water column; includes algae and often referred to as “algae”.

Plankton-Collectively all those organisms (small) suspended in the water with limited mobility in a current.

Production (productivity)-The amount or weight of organic matter synthesized by organisms from inorganic substances by autotrophs per unit time in a defined volume of water.

Rotifera (Rotifer)-Phylum of very small microscopic/near microscopic form of zooplankton.

Schmidt's stability-A calculation using various stratification data to determine the amount of work (energy) needed to mix a lake deeper than the epilimnion.

Secchi depth-A measure of the relative depth of light penetration.

Soluble reactive phosphorus (SRP)-The form of phosphorus dissolved in the water that is available for uptake by phytoplankton (bioavailable).

Specific conductance-A measure of conductivity corrected for temperature (typically corrected for 25 degrees C). Conductivity is a measure of water's ability to conduct electricity and represents the concentration of ions (charged atoms) in the water.

Stratification index-A value calculated from the density of the water at various depths that reflects the degree of stratification. The higher the value, the more stable the water layers thus more stratified.

Thermocline-A depth defined large temperature change within the metalimnion.

Total phosphorus-A value that represents all forms of phosphorus in the water.

Trophic state-Enrichment state of a lake; oligotrophic, mesotrophic or eutrophic.

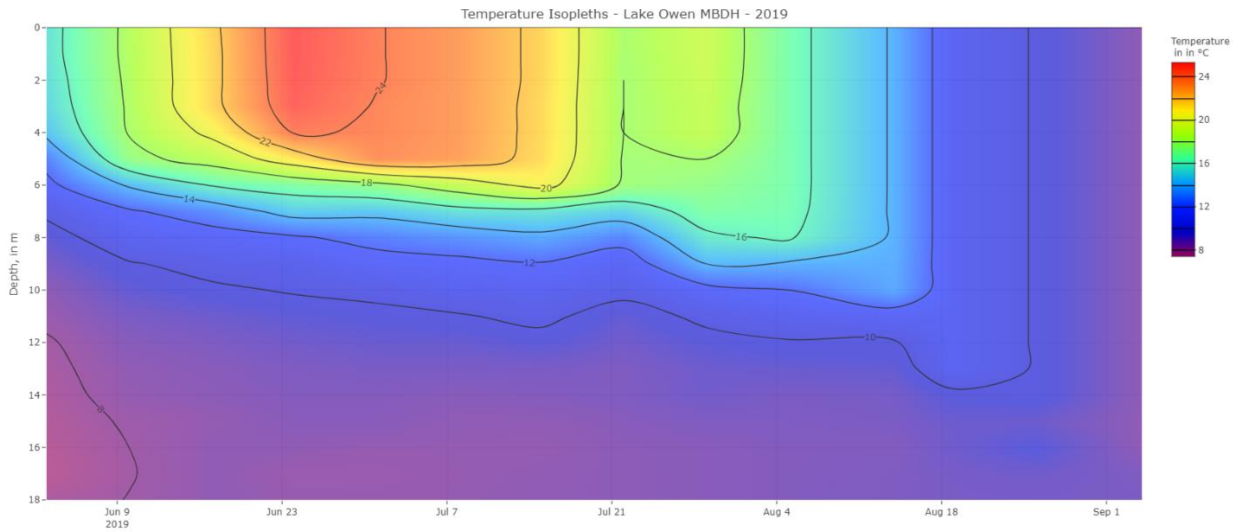
Trophic State Index (TSI)-Calculation using total phosphorus concentration, chlorophyll-a concentration, and Secchi depth to determine trophic state.

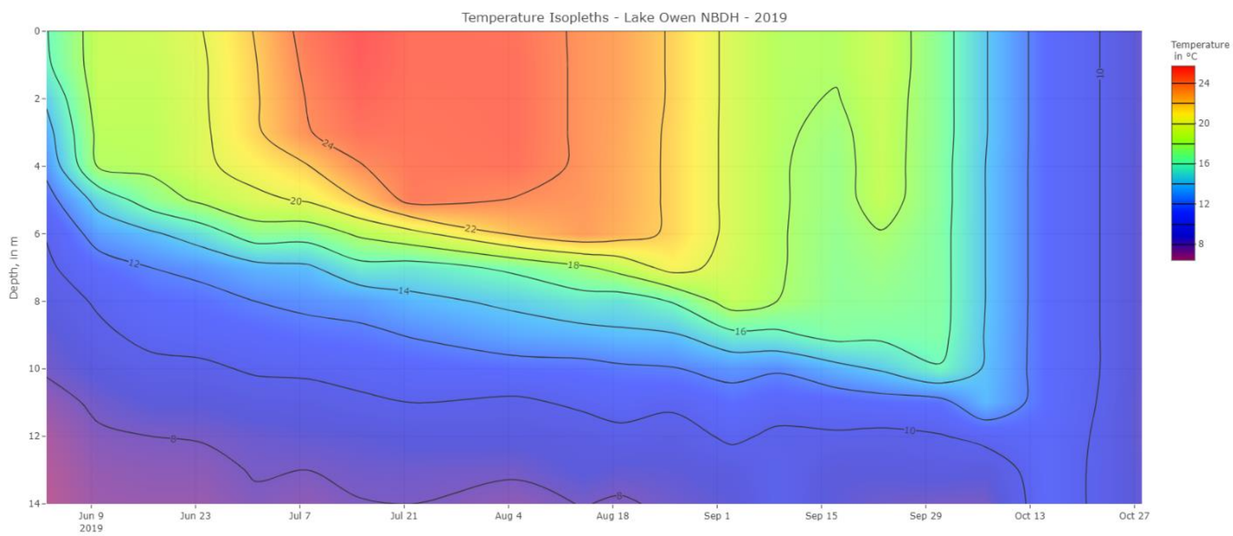
Watershed-An area of land that intercepts and drains precipitation and collects water for a particular water body.

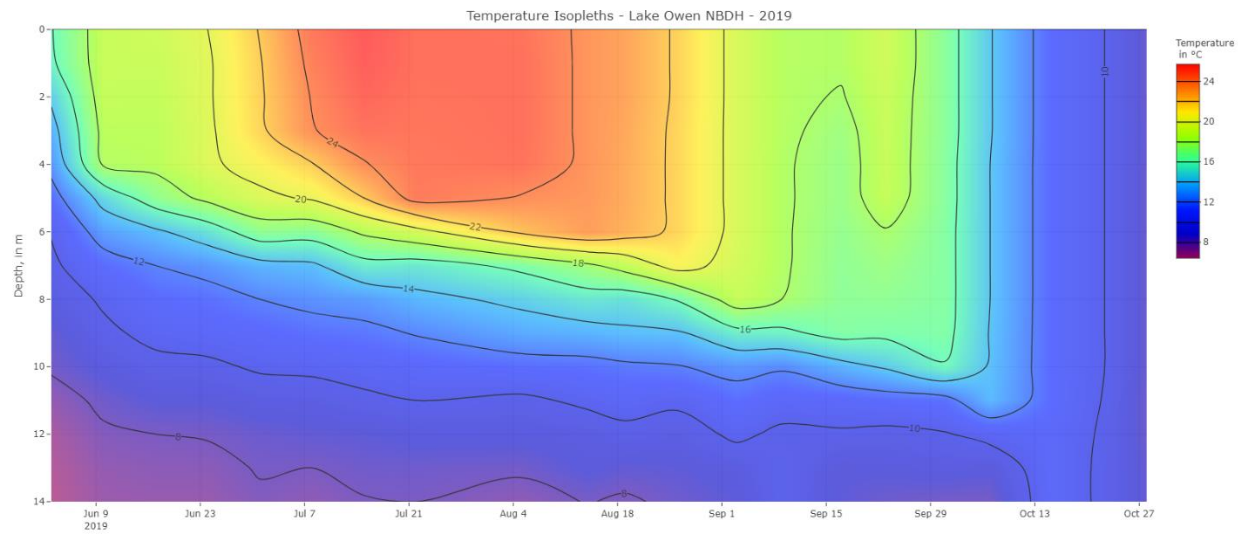
Wedderburn number-A unitless number that represents the tendency for a lake to mix based upon wind shear at the lake's surface. Values > 1 indicate no mixing and values $<<1$ indicate vertical mixing deeper than the epilimnion.

Zooplankton-Collectively, all those animals suspended in the water of an aquatic habitat which are not independent of currents and water movements.

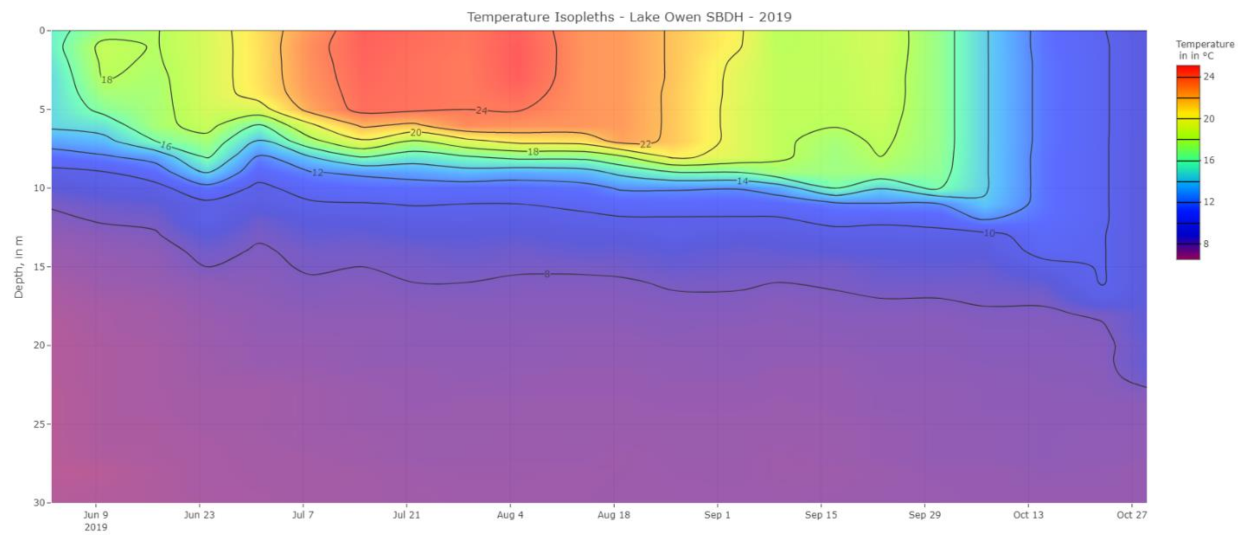
Appendix-Graphic Display of Profile Data Sets



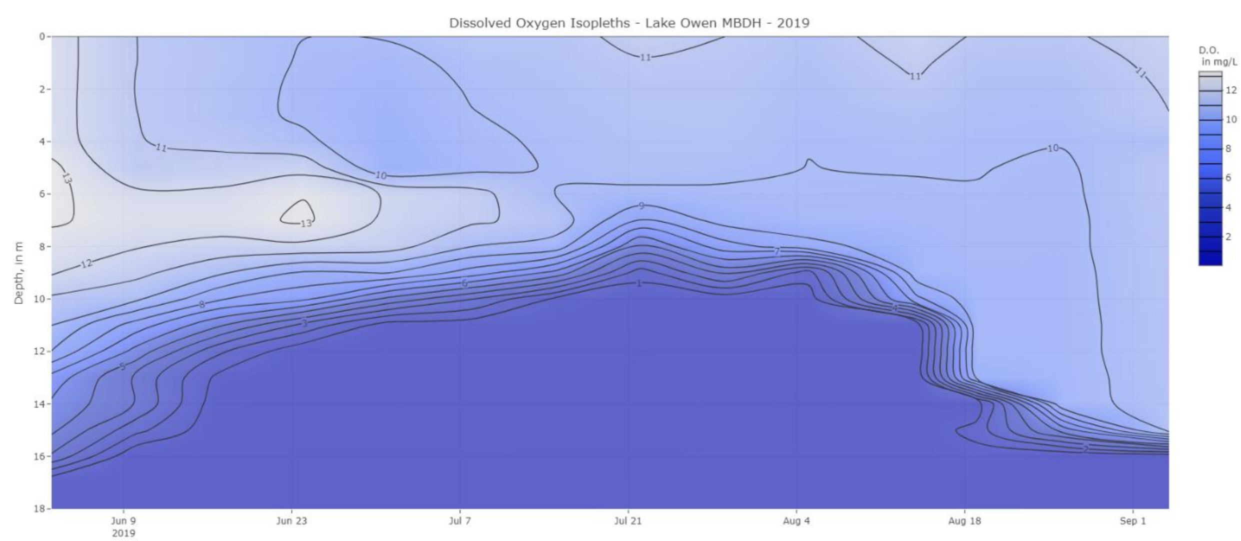




Temperature Isopleths - Lake Owen NBDH - 2019
Depth, in m
Temperature in °C
Jun 9 2019
Jun 23
Jul 7
Jul 21
Aug 4
Aug 18
Sep 1
Sep 15
Sep 29
Oct 13
Oct 27

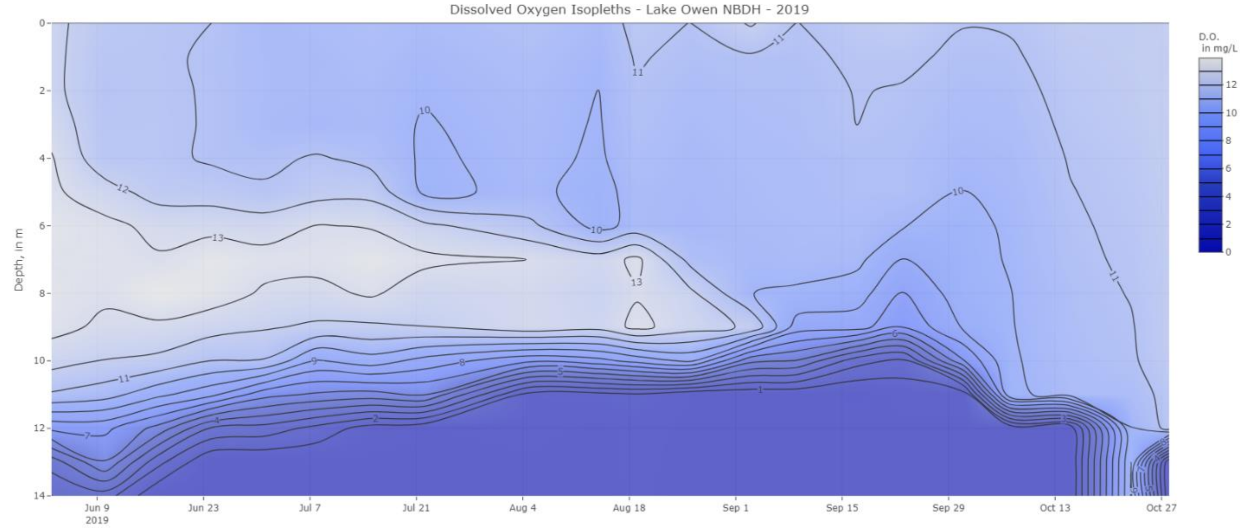


Temperature Isopleths - Lake Owen SBDH - 2019
Depth, in m
Temperature in in °C
Jun 9 2019
Jun 23
Jul 7
Jul 21
Aug 4
Aug 18
Sep 1
Sep 15
Sep 29
Oct 13
Oct 27

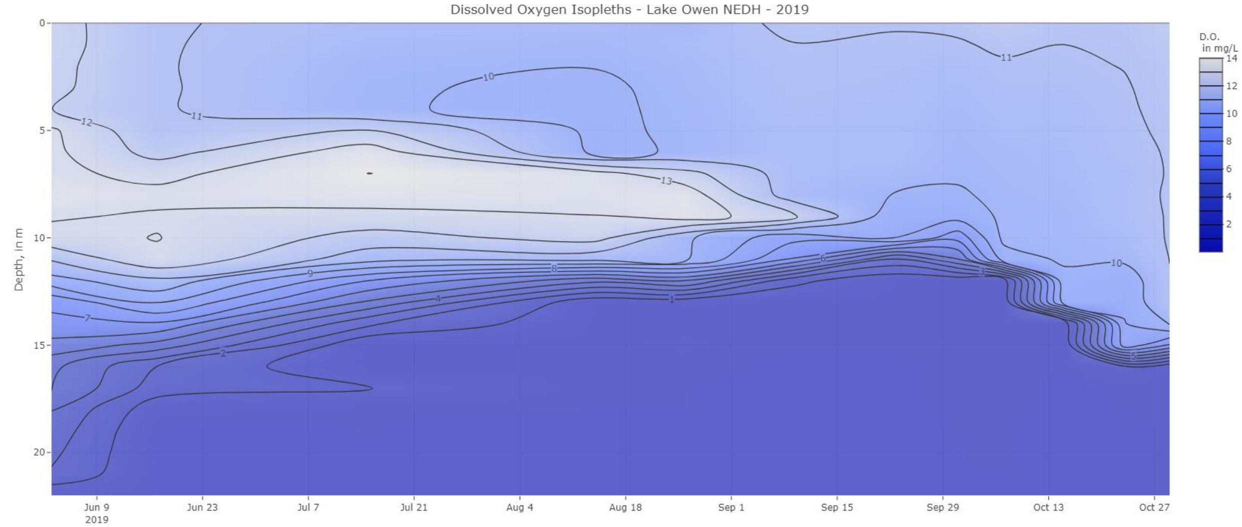


Dissolved Oxygen Isopleths - Lake Owen MBDH - 2019
Depth, in m
D.O. in mg/L
Jun 9 2019
Jun 23
Jul 7
Jul 21
Aug 4
Aug 18
Sep 1

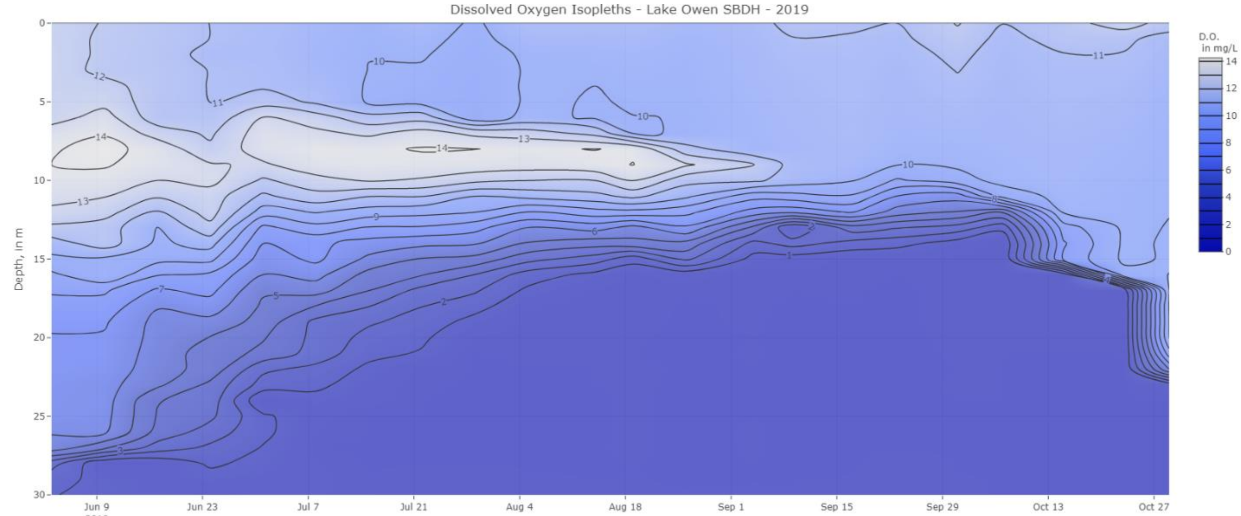
Dissolved Oxygen Isopleths - Lake Owen NBDH - 2019



Dissolved Oxygen Isopleths - Lake Owen NEDH - 2019



Dissolved Oxygen Isopleths - Lake Owen SBDH - 2019



NEDH	3-Jun	17-Jun	1-Jul	15-Jul	14-Aug	26-Aug	9-Sep	23-Sep	1-Oct	7-Oct	15-Oct	23-Oct	29-Oct
0	123.64	123.19	123.98	125.66	124.94	123.76	122.93	123.54	121.93	122.13	122.39	122.73	123.04
1	123.64	123.19	123.98	125.80	124.84	123.76	122.93	123.65	121.81	122.42	122.53	122.54	123.19
2	123.89	123.19	123.48	125.70	124.63	123.76	122.66	123.81	121.93	122.04	122.53	122.54	123.19
3	123.81	123.08	123.63	125.40	124.88	123.66	122.66	123.51	121.81	121.92	122.53	122.54	123.19
4	123.86	123.19	123.92	125.54	124.71	123.66	122.93	123.29	121.81	121.92	122.66	122.54	123.19
5	131.36	123.19	124.42	124.79	124.50	123.55	122.82	123.55	121.81	122.08	122.66	122.54	123.04
6	126.25	124.28	124.59	125.12	125.29	123.80	122.82	126.93	121.69	122.08	122.53	122.54	123.04
7	126.94	123.38	123.24	125.22	127.61	125.66	122.70	123.76	121.69	121.96	122.53	122.54	123.04
8	127.12	124.17	124.25	124.42	126.53	124.35	122.74	123.54	121.97	121.96	122.53	122.54	123.04
9	126.80	124.18	125.22	124.96	126.13	125.25	125.56	123.99	122.33	121.96	122.53	122.40	123.04
10	125.87	123.95	125.80	125.86	125.88	125.99	126.91	123.29	124.27	121.96	122.53	122.73	122.90
11	128.31	124.05	127.05	126.77	127.28	126.08	126.70	127.67	127.12	122.29	122.53	123.01	122.90
12	128.42	125.96	127.66	129.40	128.78	127.70	128.09	130.08	127.93	128.18	122.53	124.00	122.90
13	128.55	126.86	129.06	130.30	131.21	129.93	128.97	131.51	129.20	129.42	122.76	124.33	123.09
14	128.47	128.49	131.06	132.30	133.15	131.60	131.06	133.13	131.13	130.53	132.60	124.58	123.58
15	129.79	130.27		133.49	134.58	131.99	132.07	137.56	133.44	132.99	132.98	124.58	125.22
16	130.99	132.42		135.01	135.96	135.33	140.22	144.89	135.96	140.12	137.61	131.27	132.89
17	131.63	132.91		136.08	139.33	138.85	157.90	164.56	151.94	142.43	142.75	141.27	146.19
18	132.19	133.48		138.58	141.34	141.50	168.11		160.40	143.97	144.61	143.22	148.86
19	132.92	134.37		141.89	163.33	145.45	168.89		161.66	145.84	144.92	145.71	168.08
20	133.98	139.48		177.70		148.81				149.15	166.17	157.91	

NE Deep Hole Specific Conductance-2019

	3-Jun	10-Jun	17-Jun	24-Jun	1-Jul	8-Jul	15-Jul	22-Jul	5-Aug	14-Aug	19-Aug	26-Aug	3-Sep	9-Sep	17-Sep	23-Sep	1-Oct	7-Oct	15-Oct	23-Oct	29-Oct
0	125.52	125.30	125.30	125.60	125.98	126.22	126.90	125.50	125.34	126.23	125.52	125.15	124.70	125.00	124.47	125.50	123.91	124.40	125.20	124.79	125.78
1	125.37	125.07	125.30	125.57	125.75	126.04	126.95	125.50	125.10	126.23	125.31	125.15	124.70	125.00	124.47	125.50	123.91	124.27	125.20	124.93	125.63
2	124.18	124.89	125.16	125.46	125.47	125.76	126.77	125.54	125.00	126.13	125.31	125.15	124.70	125.00	124.25	125.37	123.91	124.15	125.20	124.79	125.63
3	123.88	125.25	124.79	125.62	125.08	125.95	125.64	125.48	125.10	126.03	125.35	125.19	124.59	125.00	123.49	125.41	123.67	124.15	125.06	124.93	125.28
4	123.35	124.70	124.49	125.62	125.07	126.06	126.15	125.52	125.34	126.03	125.29	124.98	124.59	125.16	125.33	125.19	123.83	124.32	125.06	124.93	125.63
5	123.66	124.79	124.65	125.18	125.33	125.95	126.13	125.46	125.23	126.28	125.08	124.98	124.59	125.16	124.63	125.34	123.83	124.32	125.06	124.79	125.63
6	124.12	125.04	124.21	124.72	124.76	125.33	126.60	128.33	125.37	127.08	125.79	124.98	124.36	125.16	125.31	125.29	124.23	124.32	125.06	124.79	125.78
7	124.48	124.79	123.99	124.14	124.99	125.10	125.39	125.74	126.36	127.94	127.43	125.83	124.56	125.04	124.65	125.40	124.23	124.32	124.93	124.93	125.78
8	124.89	125.61	124.30	124.55	125.32	125.50	126.26	127.12	126.89	128.69	128.31	127.11	127.34	125.25	125.40	125.71	124.23	124.32	124.93	125.07	125.63
9	125.28	125.61	124.94	125.19	126.13	125.77	126.74	126.33	126.57	128.46	128.03	127.47	128.64	127.37	126.26	126.24	124.52	124.62	124.93	125.07	125.63
10	125.31	126.44	125.66	126.59	126.30	127.22	128.28	127.96	129.08	131.17	130.57	130.30	130.71	131.43	132.06	130.52	127.45	124.92	124.93	125.07	125.63
11	126.84	126.87	127.14	127.28	128.90	129.12	129.42	129.36	130.13	133.20	132.70	132.50	132.33	133.45	133.02	134.30	134.96	125.66	125.06	125.97	126.43
12	128.45	127.63	128.24	129.65	130.17	130.18	131.56	131.34	130.62	133.05	132.46	133.12	132.78	137.62	134.00	134.16	134.49	133.60	137.27	126.74	126.57
13	129.21	128.34	129.11	130.46	131.72	131.79	159.46	132.45	132.52	167.37	132.94	133.30	137.15	158.80	139.01	134.73	137.58	141.23	138.36	126.51	125.87
14	152.00	129.09	129.92	131.13	152.35	132.63		143.05	140.44		140.44		171.05	164.42	155.23	144.34	147.66	149.58	138.91	126.37	137.84
15		131.60	130.75	133.11		135.06		153.87	183.33		164.14				163.47	151.01	156.67	153.40	144.11	150.49	135.94

NB Deep Hole Specific Conductance-2019

	3-Jun	10-Jun	17-Jun	24-Jun	1-Jul	8-Jul	15-Jul	22-Jul	14-Aug	19-Aug	26-Aug	4-Sep	9-Sep	17-Sep	23-Sep	1-Oct	7-Oct	15-Oct	29-Oct
0	136.86	136.10	136.63	136.71	135.77	136.50	137.66	136.34	138.05	137.76	137.40	137.07	137.41	136.28	136.44	135.22	135.44	136.31	137.86
1	136.86	136.10	136.63	136.71	135.95	136.51	137.66	136.50	137.94	137.76	137.40	137.13	137.41	136.28	136.32	135.34	135.56	136.98	138.49
2	136.66	136.23	136.63	136.82	135.84	136.37	137.63	136.46	137.94	137.66	137.40	136.59	136.69	136.46	136.39	135.34	135.56	136.63	138.49
3	136.84	136.37	136.61	136.71	135.51	136.12	137.59	136.36	137.94	137.66	137.40	136.72	136.69	136.35	136.57	135.22	135.56	136.63	138.49
4	136.59	136.75	136.56	136.71	135.86	136.35	137.65	136.16	137.84	137.66	137.57	136.50	136.58	136.30	136.46	135.22	135.56	136.63	138.49
5	136.59	136.45	136.45	137.18	137.42	136.46	137.72	136.12	137.94	137.55	137.46	136.68	136.58	136.19	136.53	135.10	135.56	136.63	138.34
6	136.42	137.41	136.33	137.28	137.26	137.41	137.17	138.32	137.84	137.55	137.46	136.68	136.58	136.37	136.67	135.10	135.44	136.50	138.34
7	136.38	136.81	137.79	137.45	137.34	137.50	138.01	137.86	140.29	137.96	137.46	136.57	136.58	136.52	136.58	134.86	135.56	136.50	138.72
8	136.47	137.05	137.37	137.68	137.64	137.87	137.87	138.86	140.07	141.45	139.12	136.46	136.46	136.19	136.56	135.05	135.44	136.85	138.72
9	137.94	139.41	137.87	137.08	138.40	138.04	137.97	139.07	140.37	139.97	135.93	141.65	139.05	136.38	137.06	136.02	135.44	136.85	138.58
10	138.09	138.78	138.88	137.25	139.12	138.95	139.41	139.46	141.85	141.49	141.23	141.05	140.98	137.66	140.44	137.11	135.31	136.85	138.58
11	138.51	139.69	139.35	139.40	139.64	139.36	140.53	139.78	142.00	142.29	142.33	142.16	141.92	141.69	142.31	142.88	136.50	136.58	138.58
12	138.95	139.84	139.59	139.26	140.72	140.26	141.60	140.55	142.38	142.74	142.60	142.60	142.88	142.73	142.93	143.46	142.25	137.01	138.58
13	139.39	140.39	139.59	142.63	141.17	140.95	141.93	141.04	143.00	144.44	142.48	143.00	143.04	143.58	143.72	143.90	144.47	138.26	138.58
14	139.74	140.44	140.19	140.08	141.23	141.51	142.24	141.55	143.14	143.97	142.92	144.12	143.28	144.23	143.83	144.84	145.56	138.86	138.58
15	139.84	140.70	140.60	140.38	141.63	141.32	142.60	141.76	144.12	146.07	142.80	144.34	144.34	145.48	144.85	144.88	145.58	144.61	138.43
16	140.35	140.65	140.70	141.24	141.88	141.82	143.27	142.31	145.24	145.24	145.45	145.30	144.97	145.89	145.51	145.81	146.10	147.21	138.43
17	140.76	141.47	141.36	141.34	142.44	142.37	143.67	143.56	145.65	145.50	145.24	145.98	145.65	146.13	147.05	148.08	147.66	148.99	138.14
18	141.02	141.73	141.62	141.75	142.70	143.19	144.53	144.53	145.91	146.21	145.35	145.95	147.41	147.29	148.63	149.82	149.54	150.28	138.67
19	141.44	141.73	141.62	142.31	142.40	143.90	145.25	144.83	147.08	147.23	146.21	147.98	148.28	149.20	149.95	150.40	150.41	151.01	138.67
20	141.28	142.14	141.88	142.31	142.96	144.31	145.40	144.98	147.50	148.25	146.93	148.73	149.03	150.68	150.54	150.99	150.56	150.86	140.18
21	141.28	141.99	141.73	142.87	142.96	143.86	145.70	145.55	149.46	148.40	148.25	148.73	150.81	151.86	151.42	151.87	151.44	151.59	139.79
22	141.28	141.99	141.73	142.57	144.24	144.73	146.12	146.42	149.58	150.04	148.25	149.16	152.30	153.05	151.72	152.17	152.02	152.19	143.20
23	141.70	142.29	141.73	143.14	144.81	145.15	146.54	146.12	150.64	151.39	151.09	151.99	153.80	153.50	152.61	152.76	152.47	152.62	152.05
24	141.70	142.29	142.03	143.14	155.45	145.60	146.54	146.12	153.04	153.34	151.84	153.35	154.70	153.95	153.21	153.06	152.62	152.47	154.72
25	141.85	142.29	142.90	143.29		145.90	146.69	146.69	154.40	155.00	153.19	154.70	155.30	155.15	154.40	153.36	153.81	152.92	156.52
26	142.01	142.14	143.06	144.01		145.90	147.42	147.15	155.15	156.36	155.61	155.76	156.21	156.51	154.71	153.66	154.11	153.37	162.67
27	142.16	144.39	144.13	144.47		146.94	148.18	147.60	155.76	157.12	157.27	156.36	158.63	158.63	155.31	154.11	156.37	153.52	171.69
28	190.83	165.75	184.86	145.08			220.78		207.87			156.66	193.33	165.60	193.83	191.01	196.88	179.50	216.47

SB Deep Hole Specific Conductance-2019

MBDH	6/3/19	6/17/19	7/1/19	7/15/19	7/29/19	8/14/19	8/26/19	9/9/19	9/23/19	10/1/19	10/7/19	10/15/19	10/23/19	10/29/19
0	137.39	136.62	135.50	136.92	136.24	137.01	136.78	136.83	137.20	135.90	136.75	138.96	139.55	139.69
1	137.39	136.62	135.35	136.82	136.14	137.22	136.68	136.83	137.09	135.90	137.01	138.96	139.69	139.84
2	137.30	136.58	135.13	136.98	136.24	137.22	136.68	137.13	137.27	135.90	136.88	139.09	139.55	139.84
3	136.96	136.42	135.03	136.70	136.37	137.01	136.74	137.00	137.30	135.79	136.75	139.09	139.69	139.84
4	138.30	136.60	137.15	136.95	136.26	136.91	136.74	136.90	137.07	135.79	136.75	139.09	139.69	139.84
5	137.27	136.68	138.23	140.32	136.55	136.87	136.70	137.09	138.17	135.67	136.75	139.09	139.55	139.84
6	137.49	138.84	139.40	140.74	142.40	144.57	139.74	137.28	137.69	135.55	136.75	139.09	139.55	139.84
7	138.48	140.00	140.33	139.80	142.10	144.86	145.87	147.20	138.49	135.86	136.75	139.09	139.55	139.69
8	139.31	139.73	140.99	142.67	143.32	145.43	145.99	155.67	141.54	137.27	136.88	139.09	139.55	139.69
9	138.77	140.25	141.72	143.87	144.14	147.03	147.51	152.75	147.36	148.97	137.09	139.09	139.55	139.69
10	139.84	140.73	144.01	145.23	146.41	149.43	149.86	152.95	152.53	151.79	138.06	139.09	139.41	139.84
11	140.18	142.10	146.23	148.87	149.20	152.48	151.27	155.40	155.30	155.05	154.67	139.09	139.55	139.69
12	140.93	144.45	148.28	151.51	151.83	156.54	153.57	159.27	158.11	158.80	158.52	139.09	139.55	139.69
13	140.88	145.55	149.40	152.34	154.66	157.98	157.98	164.79	162.27	164.97	163.24	140.19	139.55	139.69
14	141.43	144.93	149.96	153.34	157.40	161.77	161.18	166.00	165.73	172.57	171.08	156.41	139.55	139.54
15	141.54	146.48	153.44	154.20	156.97	178.93	173.37		172.61	186.37	177.76		142.08	139.54
16	142.85	147.64	153.31	157.70	166.07		188.54		186.09		204.02		157.40	159.02
17	167.66		153.45	174.34	205.56									

MB Deep Hole Specific conductance-2019