Water Quality of Hayden Lake with Special Emphasis on Mokins and O'Rourke Bays

Introduction

Hayden Lake is the second largest of Kootenai County Idaho's eight lakes. The water quality of the Hayden Lake was fully characterized by Saltero and his students (Saltero et.al, 1986) during the mid-1980s. Saltero's assessment was followed by seventeen years of monitoring by Robert Black participating in Idaho Department of Environmental Quality's citizen water quality monitoring program (Harvey 2005). Similar but more extensive water quality monitoring was completed by the Hayden Lake Watershed Association Inc. (Harvey, 2005; Harvey 2006) participating in the same volunteer program. The data from all these efforts demonstrate that Hayden Lake's central body is water low in plant growth nutrients, especially phosphorous, which limits algal growth. Phosphorous is present at an average of 7.5 micrograms total phosphorous per liter. This value persisted over seventeen years from the completion of Saltero's work through the monitoring by Black. Water quality assessment in 2005 and 2006 reflected this same average value. The total phosphorous concentration found is well in the range of a water body defined as oligotrophic. Low chlorophyll a concentration in the range of one 1 to 1.5 micrograms per liter as well as the high clarity of the water of the central body reinforce the assessment of the lake's main body.

However, Hayden Lake is not a lake unaltered by man's activities. The construction of the dike in 1910 and plugging of high infiltration areas in the lake's bottom in what is now Honeysuckle Bay altered the hydrology of the lake (Harvey 2019). Areas that would have drained after spring high discharge and become mid-and late summer pastures are now inundated year around most years. Areas of the lake like the North Arm north of Henry Point, Mokins Slough, eastern O'Rourke Bay and even Honeysuckle Bay now hold water year around as a result of the hydrologic alteration. Water quality monitoring conducted by the Hayden Lake Watershed Improvement District supported earlier results (Saltero et. al., 1986; Black 1989 -2000; Harvey (2005; 2006) that the portion of Hayden Lake north of Henrys Point is shallow, eutrophic, and algal growth is limited by nitrogen rather than phosphorous (Harvey 2020).

Water quality monitoring by the Hayden Lake Watershed Improvement District concentrated on the water quality of Mokins and O'Rourke Bays during the 2020 and 2021 monitoring seasons. Sampling stations were selected in water two to four meters in depth to assess locations inundated after construction of the dike or were at least very shallow water prior to construction of the dike. These two large bays are most likely to exhibit water quality characteristics similar to those found in the lake north of Henrys Point. As a reference to earlier water quality monitoring the mid-lake station was monitored during the 2020 and 2021 water quality monitoring seasons.

Water Quality Monitoring Objective: The objective of water quality monitoring efforts was to assess whether the large bays Mokins and O'Rourke exhibit water quality characteristics more akin to the main body of the lake or its North Arm, the area north of Henrys Point.

Methods and Materials:

The methods used to sample, the materials used to prepare and transport and the laboratories analyzing the samples were essentially identical the those used to obtain the data and results reported by Harvey (2020). Sampling locations except for the mid-lake station were changed.

Water quality samples were collected bi-monthly late April and through September. Lake Watershed Management Inc. collected the samples under contract to the district and supplied these samples to Silver Valley Laboratory (2195 Ironwood Ct., Ste. C Coeur d'Alene, ID 83814), Am Test Inc. (13600 NE 126TH PL Suite C Kirkland, WA 98034) and Advanced Eco-Solutions Inc. (25011 E Trent Ave. Newman Lake, WA 99025).

Precipitation received during 2020 and 2021 was gauged using two sources of data; monthly precipitation for each water year between October through May and snow pack water equivalent for the same period. Precipitation over this time frame best estimates the relative amount of water together with the nutrients carried from the watershed into the lake. Unfortunately, no precipitation or snow pack recording stations are located in the Hayden Lake Watershed. The closest precipitation station is at Boyington Field three miles west of the lake. However, the orographic effect of elevation creates greater precipitation on the high slopes of the watershed as compared to the air field at low elevation and in the rain shadow of Mount Spokane. The two snow gauging stations operated by the Natural Resource Conservation Service (NRCS) closest to Hayden Lake are located on Ragged Mountain and on Mosquito Ridge near the head of the North Fork Coeur d'Alene watershed. Totals from these two Snowtel Stations were averaged to provide an estimate snow pack equivalent stored for the effective period.

Three locations were monitored for the two consecutive years (figure 1). These are the Mokins Bay (47.783958N, -116.673821W), O'Rourke Bay (47.759157 N, -116.680957W), and the mid-lake station (47.754961N, -116.744321W) that was sampled by Soltero, Black and Harvey and the district.

A Eureka Manta field water quality monitoring unit (model 40) was used to collect temperature, pH, dissolved oxygen and conductivity data. The Manta output was downloaded onto the laptop computer as Excel files. Water clarity was measured with a Secchi Disc.

Water quality samples were collected as water column composite samples with a Kemmerer Sampler and placed into a churn splitter. Samples were collected a meter below the surface and then at two meters intervals until a meter above the lake bottom at the Mokins Bay, and O'Rourke Bay sampling locations. At the mid-lake station sample collection terminated at 19 meters. Once samples were thoroughly mixed, water nutrient samples were drawn. A Nitrite-Nitrate, Ammonia and Total Phosphorous sample was placed into new clean 250 ml polyethylene sample bottles supplied by the laboratory and with sulfuric acid added as preservative. A separate filtered (<0.45 um) sample was prepared for total dissolved solids and ortho-phosphate analysis. Water samples were stored in an ice chest with ice packets (zero degree centigrade) and delivered overnight to the laboratory. Chlorophyll samples were collected in brown (darkened) polyethylene bottle supplied by Advanced Eco-Solutions. Chlorophyll samples were held in the ice chest. Chlorophyll samples were delivered the day of sampling to Advanced Eco-Solutions. Plankton samples were placed in a tin foil covered one liter polyethylene supplied by Advanced Eco-Solutions. The sample bottle contained Lugol's preservative solution. These samples were placed on ice and delivered to Silver Valley Laboratories for filtering. Preserved filters were supplied to Advanced Eco-Solutions for analysis of the plankton present.

Figure 1: Water quality sampling sites

Water quality samples were analyzed for Total phosphorous (Am Test using method SM 4500 PF); ortho-phosphorous (Am Test using method SM 4500 P E); ammonia (Am test using method EPA 350.1); nitrite-nitrate (Am Test using method EPA 300.0); persulfate nitrogen (Am Test using method SM#20 4500-N C) and total dissolved solids (Am Test using method SM 2540C. Am Test reported out data in micrograms per liter.

Phytoplankton samples were preserved in the field in acid Lugol's iodine preservative and shipped to Advanced Eco-Solutions Inc. in Newman Lake, WA for enumeration. The samples were gently shaken for 60 seconds and poured into 25 mL settling chambers and allowed to settle for a minimum of 3 hrs prior to quantitative enumeration using the Utermohl Method (Utermohl 1958). Counts were done using a plankton microscope. All cells within a random transect of 3.5 mm in length were counted at high power (900X magnification) that permitted a semi-quantitative enumeration of minute (<2 µ) autotrophic pico-cyanobacteria cells (1.0-2.0 µ) [Class Cyanophyceae], and of small, delicate auto-, mixo-, and hetero-trophic nano-flagellates (2.0-20.0 µ) [Classes Chrysophyceae and Cryptophyceae]. Comments on the relative density of ciliates in each sample were also noted on count sheets. Where feasible, from 250-300 cells were enumerated in each sample to assure counting consistency and statistical accuracy (Lund et al. 1958). The compendium of Canter-Lund and Lund (1995) was used as a taxonomic reference. The results were presented as cells/mL and bio-volume/Liter.

Chlorophyll samples were held in the ice chest and delivered to SVL Analytical for filtering through a 0.75 um nominal glass fiber filter. The filters were frozen and delivered to Advanced Eco-Solutions Inc. where

they remained frozen until analyzed. The samples were analyzed following EPA method 445.0 and reported in Chlorophyll a in ug/L.

Reported nutrient data was placed in Excel spreadsheets and the programs graphing function used to create simple line graphs for each sampling location. Non-detection values were recorded for graphing at one-half of detection.

Quality Assurance/Quality Control:

The Manta field monitor was calibrated before each sampling event using standard solutions. Hydrogen ion concentration (pH) was calibrated with pH 7.0 and pH 10.0 solutions. Conductivity was calibrated with a standard 957 micro-Siemans solution. Dissolved oxygen was calibrated with an oxygen saturated solution. Pressure sensors were calibrated a standard barometric pressure.

All sample containers were supplied clean by the participating laboratories. All sampling equipment and sample containers were rinsed three times with the sample water before the sample was placed in the container. All containers were filled to the brim and then the lid placed. Chain of custody forms were prepared documenting each sample. Samples were delivered to the participating laboratory the same day in the case of Silver Valley Laboratory and Advanced Eco-Solutions and overnight in the case of AmTech.

Results:

Physical Measurements:

Specific conductivity, pH and clarity:

Specific conductivity, pH and clarity measurements were in the ranges observed in earlier monitoring of the lake. Clarity measurements are only relevant at the mid-lake station because the two bay stations are shallow allowing light to reach the bottom. Clarity of the lake was slightly higher in 2021 as compared to 2020.

Table 1: pH, conductivity, clarity and dissolved oxygen average and variances of the three monitoring stations on Hayden Lake in 2020

Physical Measurement	Station	Average	Maximum	Minimum
pH	Mid-Lake	8.0	8.9	6.9
	Mokins Bay	8.3	9.2	7.2
	O'Rourke Bay	8.0	9.1	6.9
Conductivity (uS)	Mid-Lake	63	68	61
	Mokins Bay	70	77	67
	O'Rourke Bay	59	72	34
Clarity (meters)	Mid-Lake	7.4	9.0	5.0
Dissolved Oxygen	Mid-Lake	9.8	12.0	7.9
	Mokins Bay	9.9	12.2	8.5
	O'Rourke Bay	9.6	11.8	7.8

Note: Mokins and O'Rourke Bay Stations do not exceed 4 meters bottom always visible

Table 2: pH, conductivity, clarity and dissolved oxygen average and variances of the three monitoring stations on Hayden Lake in 2021

Physical Measurement	Station	Average	Maximum	Minimum
pH	Mid-Lake	7.9	8.8	7.2
	Mokins Bay	8.5	9.8	7.5
	O'Rourke Bay	8.6	9.5	7.4
Conductivity (uS)	Mid-Lake	61	67	42
	Mokins Bay	70	90	45
	O'Rourke Bay	54	67	26
Clarity (meters)	Mid-Lake	8	10	6
Dissolved Oxygen	Mid-Lake	11.5	19.9	8.8
	Mokins Bay	11.3	13.5	9.5
	O'Rourke Bay	11.5	14.9	10.4

Note: Mokins and O'Rourke Bay Stations do not exceed 4 meters bottom always visible

Water Temperature:

Temperature results from the mid-lake station indicate the normal stratification of the lake through each summer season. Water temperature was nearly uniform with depth early in the season. Temperature stratification increased through mid -summer as expected. Stratification peaked two weeks earlier in 2021, likely due to the second summer season's warmth. As the summer heat waned in late August and September water temperature declined.

The Mokins and O'Rourke Bay sites were in much shallower water; two to three meters maximum. Water temperatures at these two locations reflected those of the upper layer of the lake's water. Shallow water in 2021 precluded measurement at two meters after two sampling sessions. As a result of the shallow character of the sites, water temperature preformed similar to the North Arm stations both years.

Figure 2: Water temperature profiles of the mid-lake monitoring station 2020

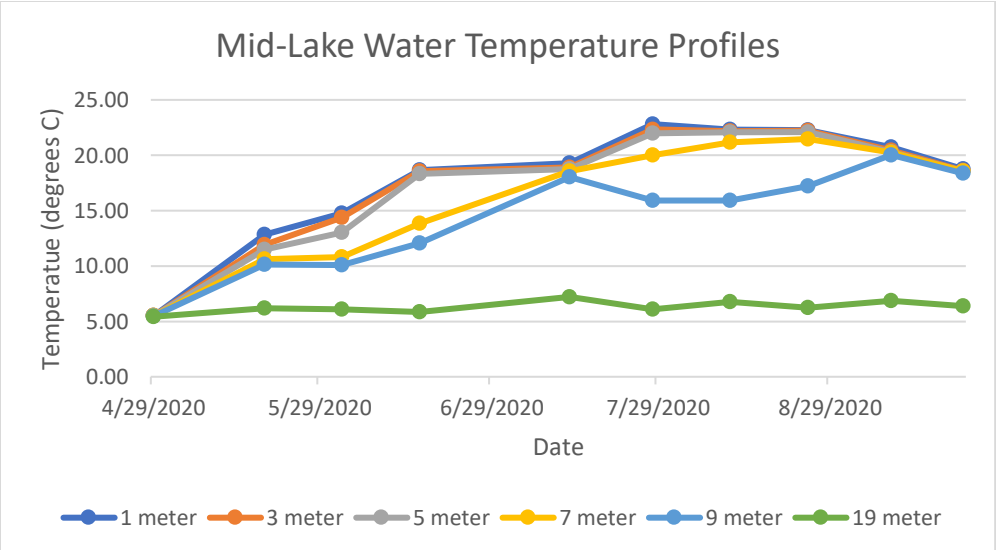


Figure 3: Water temperature profiles of the mid-lake monitoring station 2021

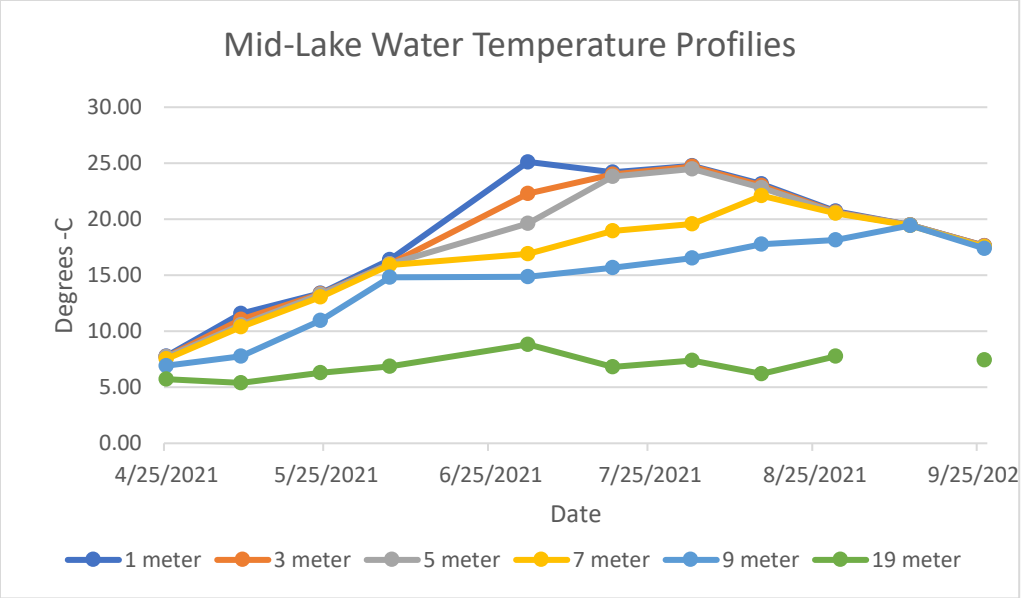


Figure 4: Water temperature at Mokins Bay Monitoring Station 2020

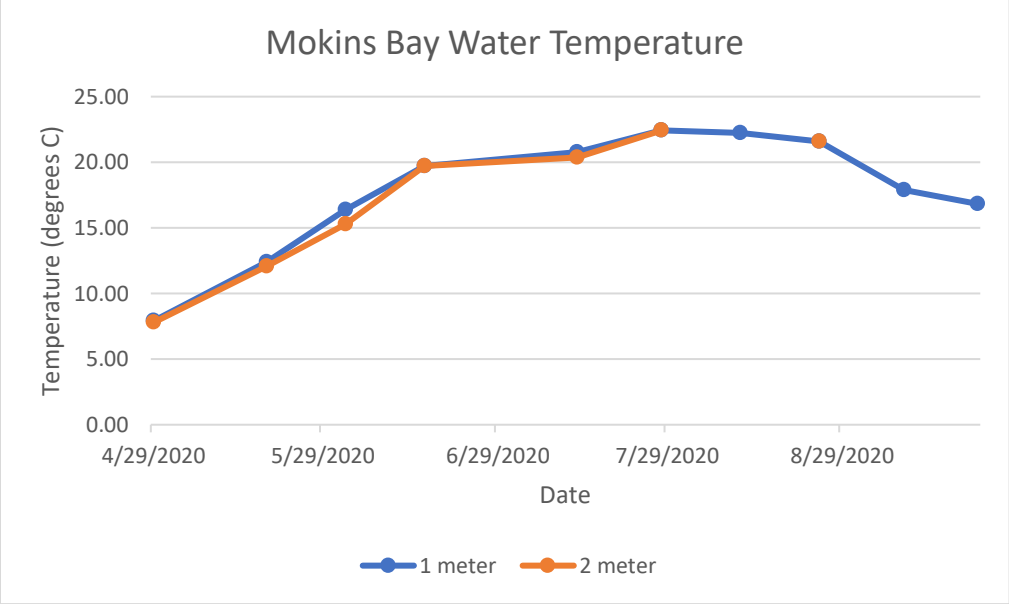


Figure 5: Water temperature at Mokins Bay Monitoring Station 2021

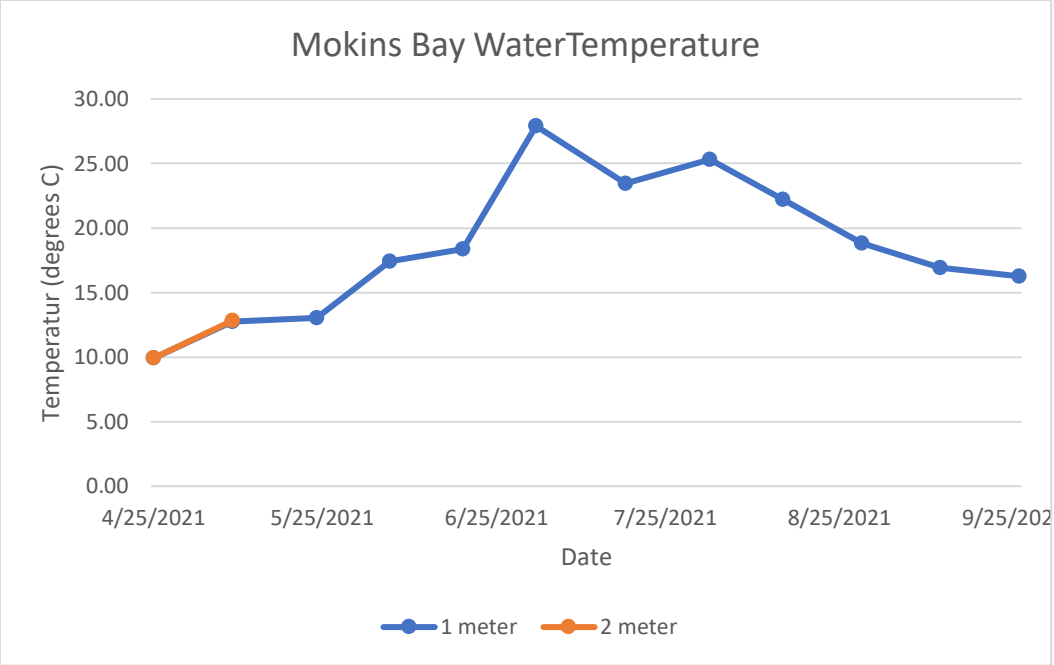


Figure 6: Water temperature at O'Rourke Bay Monitoring Station 2020

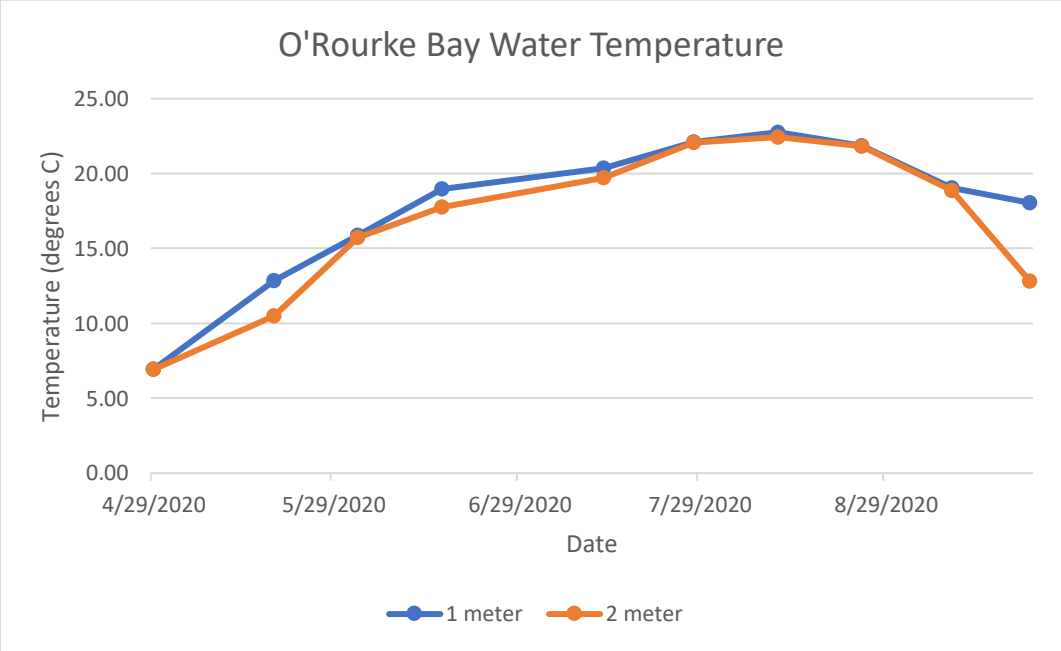
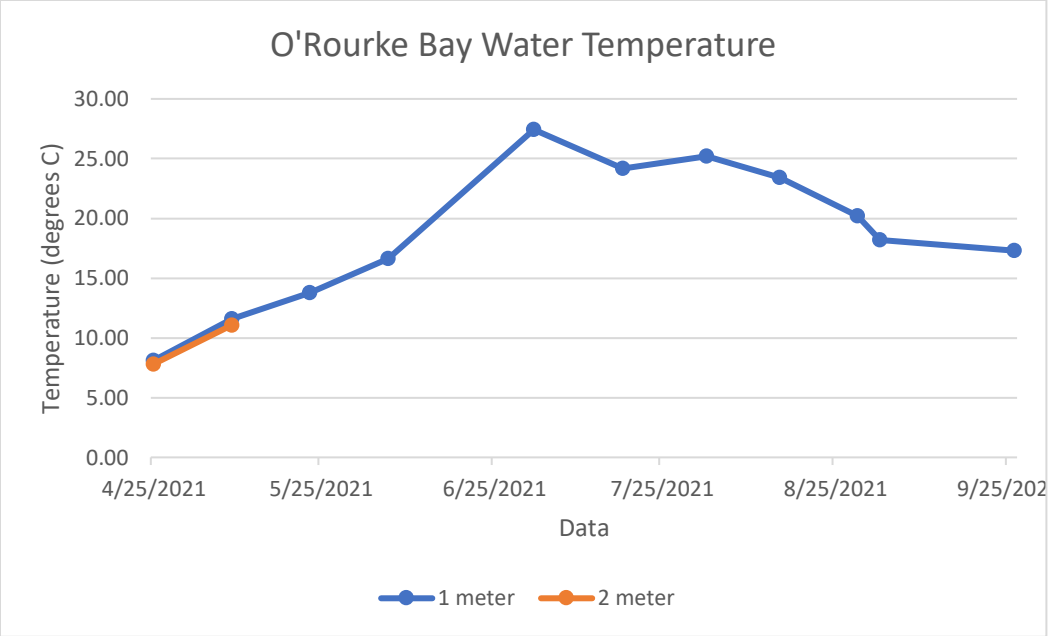


Figure 7: Water temperature at O'Rourke Bay Monitoring Station 2021



Dissolved Oxygen:

Dissolved oxygen monitored through both years was well above the concentration and percent saturation required by water quality standards at all levels of the mid lake, Mokins and O'Rourke Bay monitoring stations. The lowest percent saturation of the entire data set collected was 93% of saturation. Both the Mokins and O'Rourke Bay stations were sufficiently shallow to allow dissolved oxygen concentrations from wind agitation of the water column. The dissolved oxygen profiles of the mid-lake station demonstrated the relatively good condition of the lake's main waterbody. Dissolved oxygen increased with depth at maximum stratification. Dissolved oxygen decline (sag) with depth is indicative of water quality issues in a lake's waters. This condition was not observed.

Figure 8: Mid-Lake monitoring station dissolved oxygen profile at maximum stratification 2020

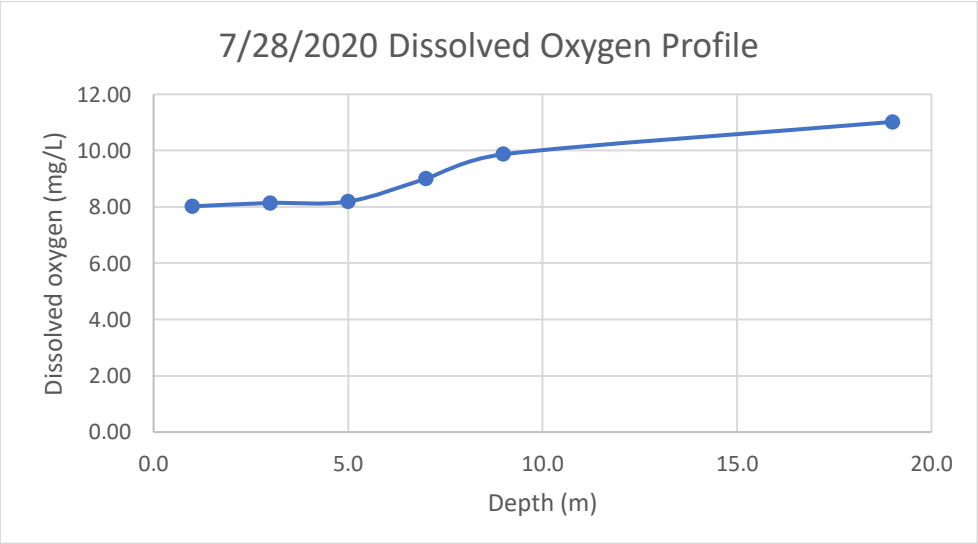
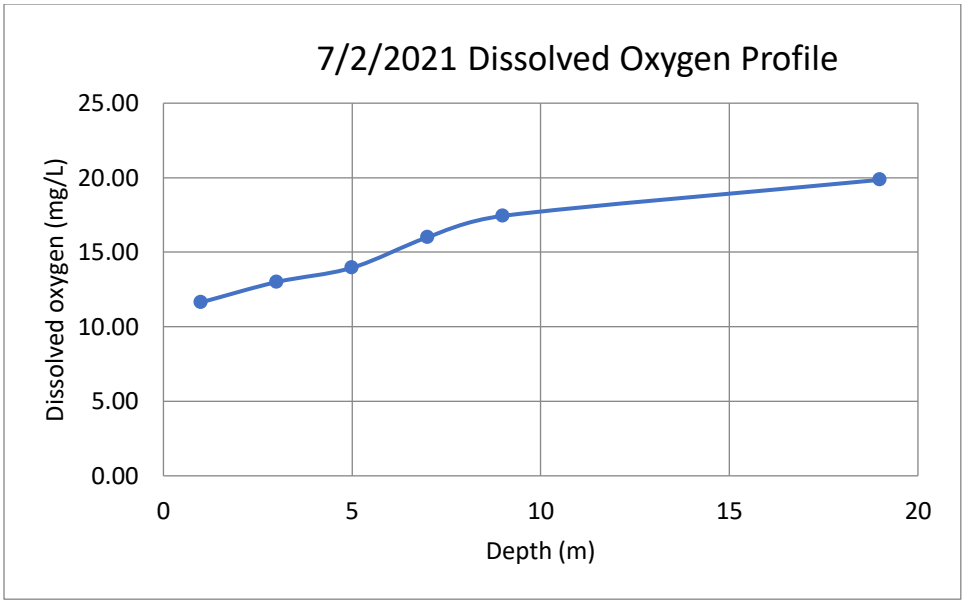


Figure 9: Mid-Lake monitoring station dissolved oxygen profile at maximum stratification 2021



Watershed Precipitation and Snow Pack:

Watershed precipitation and snow pack water equivalent were estimated from measuring stations outside the watershed. The precipitation and average snow pack equivalent received over the period of October to May before the monitoring year maximum discharge is provided in Table 3. The Snowtel data clearly demonstrates the orographic effect of high elevation. Both the Snowtel and airport data demonstrate the same pattern of the higher precipitation in 2020 and remarkably lower precipitation in 2020. Although snowpack was lower in 2021, it was failure to receive precipitation during the late winter, spring and early summer months of 2021 that likely contributed to the lower 2021 lake water levels. No precipitation was recorded at Boyington Field between April and October 2021.

Table 3: October to May water year precipitation at Boyington Field and average precipitation equivalent for the Ragged Mountain and Mosquito Ridge Snowtel Stations.

Station	Water Year	Precipitation (cm)
Boyington Field	2020	45
	2021	26
Rugged-Mosquito Average	2020	126
	2021	100

The perceived higher temperatures of 2021 as compared to 2020 is not borne out from the temperature data recorded at Boyington Field, the closest recording station to Hayden Lake. The yearly median temperature in 2021 was two degrees Fahrenheit (1 degree centigrade) higher compared to 2020 (2020-51.4; 2021 -53.7). However, the median temperature for the period of May through August was warmer in 2020 than in 2021 (2020- 70; 2021-69). A major element of driving surface water evaporation is air temperature. If weather conditions drove the low 2021 lake levels, the existing weather data suggests lack of precipitation rather than high temperatures drove the lower lake levels

Plant (Algae) Growth Nutrients:

Plant growth in general and specifically the growth of planktonic algae in a lake is dependent on nine macro-nutrients and a host of micro-nutrients required in vanishingly low concentrations. Of the nine macro-nutrients, phosphorous and nitrogen are capable of limiting the growth of algae in most lakes including those of North Idaho. Typically, phosphorous as ortho-phosphate limits algal growth in lakes, however, in those situations where phosphorous is not the limiting nutrient, nitrogen in the chemical forms of nitrite, nitrate and ammonia may limit algal growth. This is most often the case in eutrophic lakes where total phosphorus exceeds 25 micrograms per liter and ortho-phosphate the chemical form required by plants is measurable.

Phosphorous:

Total phosphorous measured at the three monitoring stations during the 2020 monitoring year is graphed in figure 10 and the average and variances are provided in Table 4., while total phosphorous measured at the three monitoring stations during the 2021 monitoring year is graphed in figure 11 and the average and variances are provided in Table 5. The mid-lake station provided total phosphorous

Figure 10: Total phosphorous at the mid-lake and two bays station during 2020

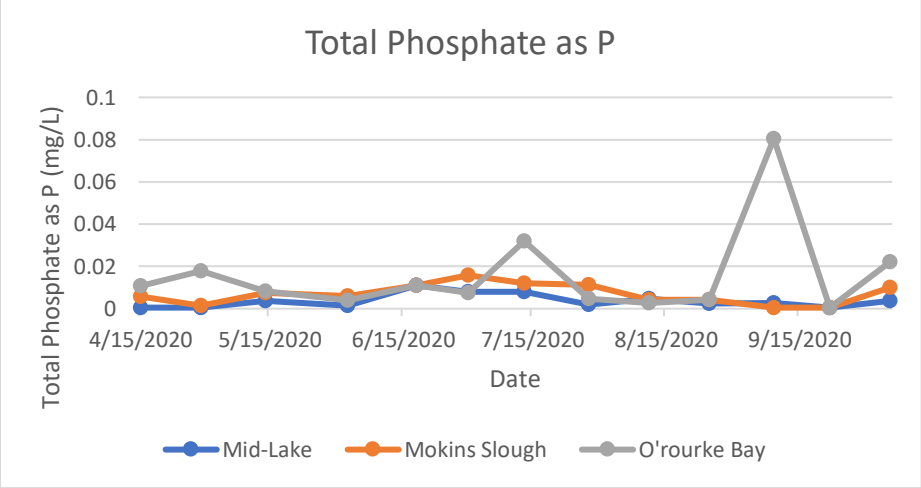


Table 4: Total Phosphorous data statistics (ug/L) 2020

Station	Average	Maximum	Minimum
Mid-Lake	4	11	0.5
Mokins Bay	7	16	0.5
O'Rourke Bay	16	80	0.5

Detection: 1 ug/L; half detection recorded for no detection

Figure 11: Total phosphorous at the mid-lake and two bays station during 2021

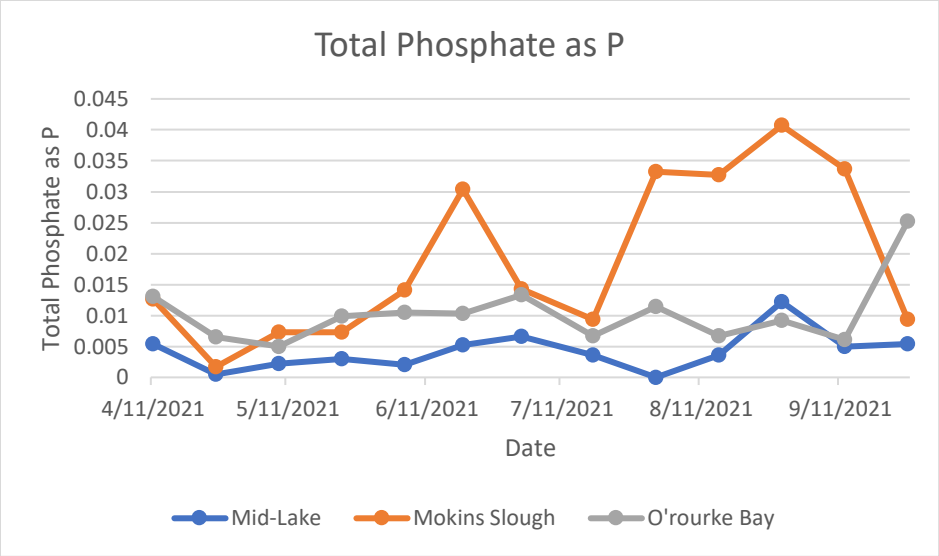


Table 5: Total Phosphorous data statistics (ug/L) 2021

Station	Average	Maximum	Minimum
Mid-Lake	5	12	0.5
Mokins Bay	19	41	2
O'Rourke Bay	10	25	5

Detection: 1 ug/L; half detection recorded for no detection

values typical of years past in both years. Averages both years were well below the long running average of 7.5 micrograms per liter. Total phosphorous values from both Mokins and O'Rourke Bays varied between 2020 and 2021. The values during 2020 in both bays were relatively low with but a few notable exceptions, while the values were much higher especially for Mokins Bay during 2021. During 2020 the bays total phosphorous values were more similar to the main lake, while the next year the bays and especially Mokins Bay performed in a manner more similar to the North Arm. The higher total phosphorous levels in 2021 are likely related to the shallow water and dewatering of a large part of the bays especially, Mokins Slough.

Ortho-phosphate is the chemical compound of phosphorous absorbed by plants including planktonic algae. Ortho-phosphorous is present in natural waters in concentration either below or just above the level of detection, 1 microgram per liter. Ortho-phosphate levels averaged just at detection at all monitoring stations in 2020. During 2021 the averages doubled. However, the higher averages are supported by a single data point. In addition, the high value does not occur at the same time total phosphate increases later in the monitoring year. Given the unnaturally high ortho-phosphorous levels measured all the monitoring stations in this one instance, it is likely these data were a product of contamination or laboratory error. Unfortunately, the questionable data was not detected in time for a retest of the samples. Hence the total data set is provided. If the data points for this single date are excluded, the ortho-phosphorous values during 2021 are similar to those of the previous year.

Figure 12: Ortho-phosphorous at the mid-lake and two bays station during 2020

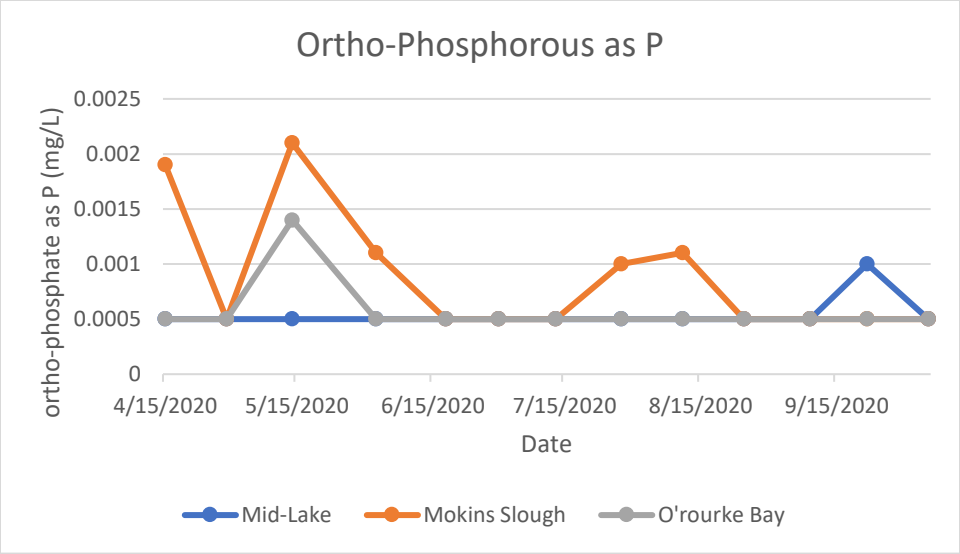


Table 6: Ortho-phosphorous data statistics (ug/L) 2020

Station	Average	Maximum	Minimum
Mid-Lake	1	1	0.5
Mokins Bay	1	2	0.5
O'Rourke Bay	1	1	0.5

Detection: 1 ug/L; half detection recorded for no detection

Figure 13: Ortho-phosphorous at the mid-lake and two bays station during 2021

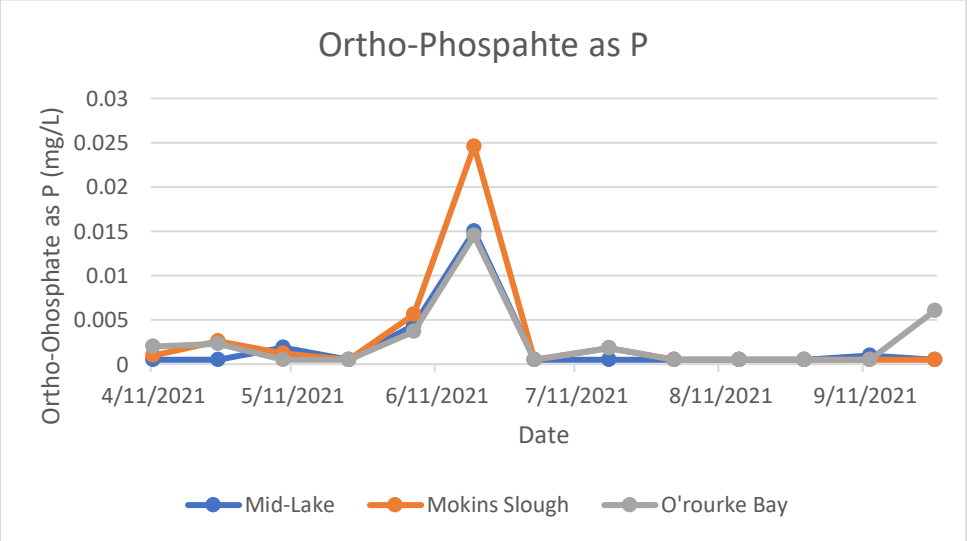


Table 6: Ortho-phosphorous data statistics (ug/L) 2021

Station	Average	Maximum	Minimum
Mid-Lake	2	15	0.5
Mokins Bay	3	25	0.5
O'Rourke Bay	2	15	0.5

Detection: 1 ug/L; half detection recorded for no detection

Nitrogen Plant Growth Nutrients:

Nitrite-Nitrate:

The primary source of nitrogen to plant (algal) metabolism is nitrate, the inorganic nitrogen compound in which nitrogen is fully oxidized. Some nitrite a less oxidized compound of nitrogen may also be present, but in much lower concentrations. These basic nitrogen sources are typically measures in water as the concentration of the composite nitrite-nitrate. Total nitrite-nitrate was measured at the three monitoring stations. The data from the 2020 and 2021 monitoring seasons are graphed in figure 14 and 15, respectively. The average maximum and minimum values measured at each station are provided in table 7 and 8, respectively.

Figure 14: Total nitrite-nitrate concentrations found at each monitoring stations through the 2020 season.

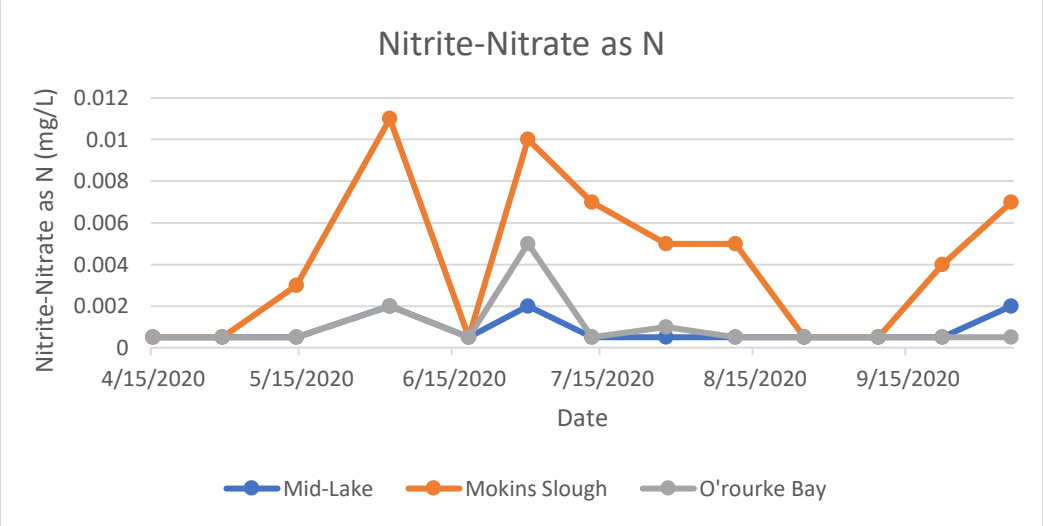


Table 7: Nitrite-nitrate data statistics (mg/L) 2020

Station	Average	Maximum	Minimum
Mid-Lake	0.001	0.002	0.0005
Mokins Bay	0.004	0.011	0.0005
O'Rourke Bay	0.001	0.005	0.0005

Detection: 0.001 mg/L; half detection recorded for no detection

Figure 15: Total nitrite-nitrate concentrations found at each monitoring stations through the 2021 season.

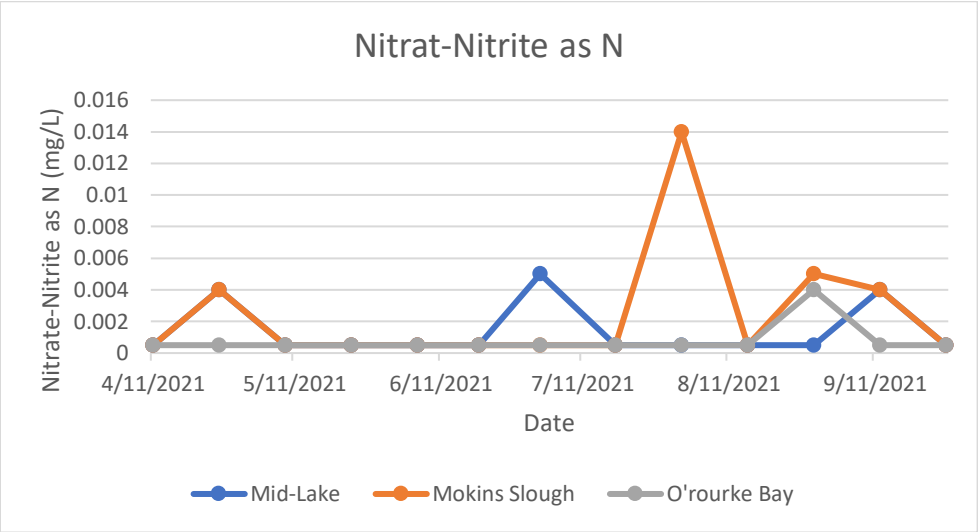


Table 8: Nitrite-nitrate data statistics (mg/L) 2021

Station	Average	Maximum	Minimum
Mid-Lake	0.0014	0.0050	0.0005
Mokins Bay	0.0024	0.0140	0.0005
O'Rourke Bay	0.0008	0.0040	0.0005

Detection: 0.001 mg/L; half detection recorded for no detection

Nitrite-Nitrate concentrations remain low at the mid-lake station during both years with slightly higher values in 2021. Nitrile concentrations are higher in the bays with Mokins Bay far exceeding the values found in O'Rourke Bay. Late in the 2021 season nitrite-nitrate concentrations appear to increase. Unlike the situation often observed in the northern arm of the lake, the nitrile concentrations do not slip constantly below detection during the summer months.

Ammonia:

The other form of inorganic nitrogen that algae can absorb from the water is ammonium ion, which is nitrogen in its most reduced form. Ammonium ion measured as ammonia is rather uncommon in lake water or elsewhere in the environment. Ammonia is rather quickly oxidized to nitrite and further to nitrate. Ammonia is only typically detectable when organic matter is decaying in the water column. The concentration of ammonia detected from water at the three monitoring stations during 2020 and 2021, respectively are graphed in figure 16 and 17, respectively. The average maximum and minimum values measured at each station are provided in table 9 and 10, respectively. Aquatic weed management with herbicides results in the death and decay of plant material, which in turn releases ammonia. The dates of herbicide application, the herbicide applied and its period of lethality are included on the ammonia graphs.

Figure 16: Ammonia concentration found at each monitoring stations with all herbicide treatments noted through the 2020 monitoring season.

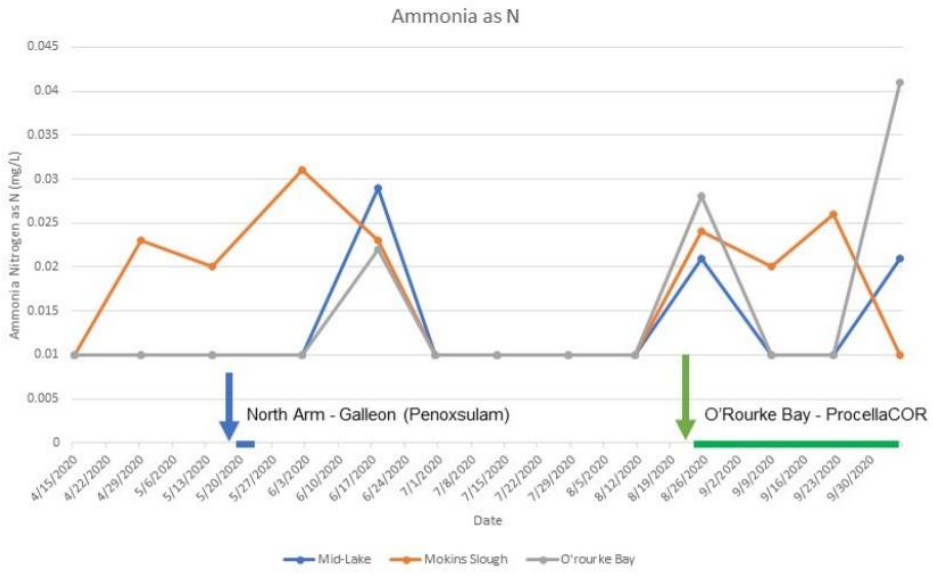


Table 8: Ammonia data statistics (mg/L) 2020

Station	Average	Maximum	Minimum
Mid-Lake	0.013	0.029	0.01
Mokins Bay	0.017	0.031	0.01
O'Rourke Bay	0.015	0.041	0.01

Detection: 0.02 mg/L; half detection recorded for no detection

Figure 17: Ammonia concentration found at each monitoring stations with all herbicide treatments noted through the 2021 monitoring season.

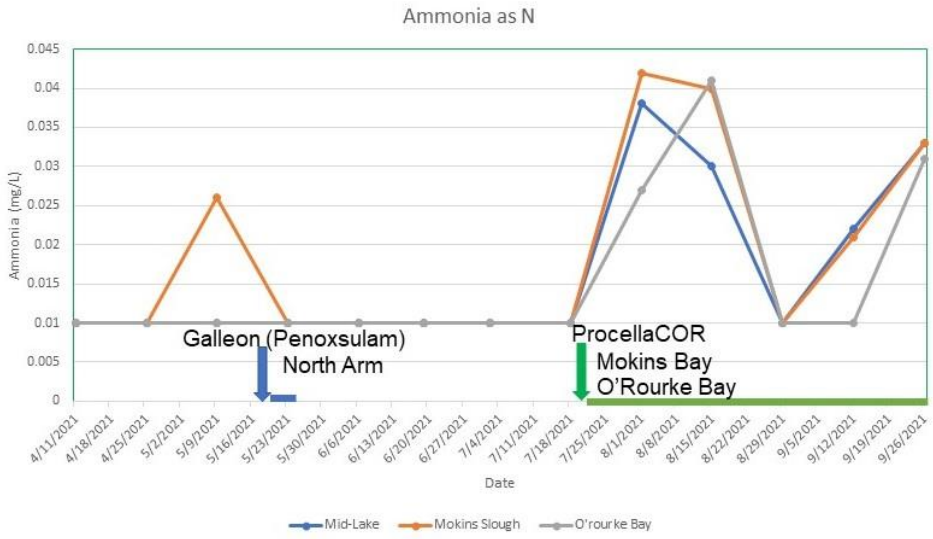


Table 9: Ammonia data statistics (mg/L) 2021

Station	Average	Maximum	Minimum
Mid-Lake	0.016	0.038	0.01
Mokins Bay	0.019	0.042	0.01
O'Rourke Bay	0.015	0.041	0.01

Detection: 0.02 mg/L; half detection recorded for no detection

Average ammonia concentrations in both years was below the detection limit of 0.2 milligrams per liter much of the time. Ammonia levels clearly increase after ProcellaCOR treatment, which is active over a thirty-to-ninety-day period. The timing of ammonia increases in May and June in 2020 and in Mokins Bay in 2021 are not aligned with the Galleon treatments in time or location. These ammonia spikes are more likely associated with the die off of the annual spring diatom bloom. The ammonia increases after PorcellaCOR has been observed elsewhere in the lake's northern arm. These results from further south in the lake support those observations. The fact that mid-lake ammonia increases for at least a short time may be due to the many locations treated in late July 2021 (Mokins Slough, Lees Point/Preston Bay, O'Rourke Bay, Windy Bay, South of Clark Point, Berven Bay). Nitrogen concentrations as either nitrite-nitrate and/ or ammonia were sufficient to preclude blue-green algae blooms.

Organic Nitrogen:

Organic nitrogen was measured indirectly. The total nitrogen in water samples was measured using the persulfate method. This method measures the nitrite-nitrate, ammonia and the combined or organically bound nitrogen present in the sample. By subtraction of the nitrite-nitrate and ammonia concentrations independently measured from the total nitrogen, the organic nitrogen present can be calculated. The organic nitrogen is an assessment of all nitrogen combined in organic compounds; however, the great majority of the organic nitrogen will be housed in living biomass. Hence the organic nitrogen parameter is a useful assessment of the relative amount of biomass present in the waters of each station. However, the value is calculated and such mathematically derived values can be below zero. These are artifacts of variance of parameters reflected in the calculation. Hence organic nitrogen reflects large trends, but small variances are likely not significant.

The total persulfate nitrogen graphs are in Appendix A together with the average, maximum and minimum values. The organic nitrogen values calculated from the 2020 and 2021 monitoring data are plotted in figures 18 and 19, respectively. Organic nitrogen levels rise early in the 2020 monitoring season and then generally stabilize as would be expected. A similar pattern occurs in during the 2021 monitoring season, but is interrupted in early August with values declining to zero. As stated earlier, organic nitrogen is a calculated perimeter. The calculated subject to the change if the input perimeters. In early August 2021, PercellaCOR treatment of several bays including Mokins and O'Rourke Bays caused the death and subsequent decay of aquatic vegetation. The resultant rise in ammonia and to a lesser extent nitrite-nitrate is subtracted from persulfate nitrogen content providing a smaller number. The weakness of calculated organic nitrogen assessment is its dependence of sometimes variable input. Chlorophyll a is for this reason a superior measure of at least algal biomass.

Figure 18: **Calculated organic nitrogen values for the 2020 monitoring season.**

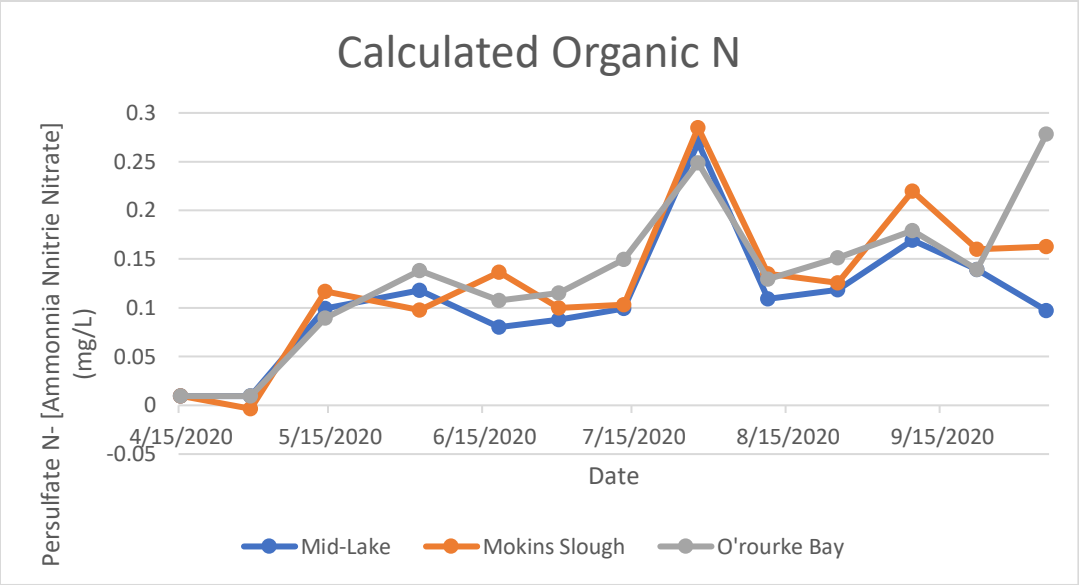
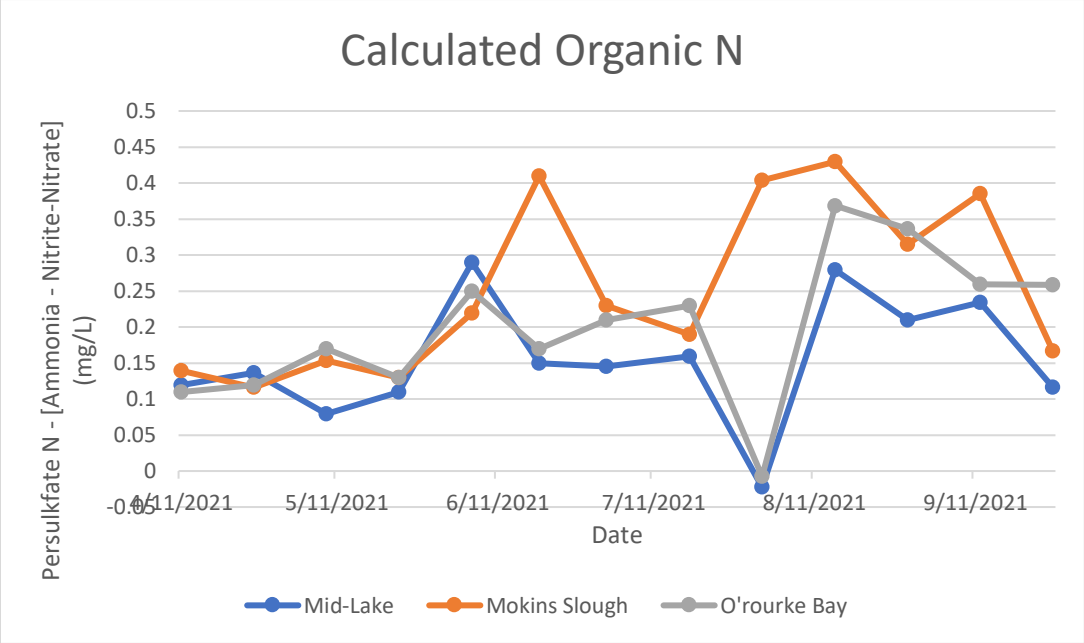


Figure 19: **Calculated organic nitrogen values for the 2021 monitoring season.**



Chlorophyll a:

Chlorophyll a concentrationss are used as an indicator of the standing crop of phytoplankton within a system. It can be used as a rough surrogate for primary productivity, but that is typically not advised due to numerous food web interactions that can alter the chlorophyll a concentration. The higher the chlorophyll a concentration the higher the standing crop of phytoplankton. Hayden Lake is considered

to be a low nutrient (oligotrophic) water. As such, we would expect to see chlorophyll a concentrations less than 3.0 ug/L. Values greater than 3.0 ug/L are indicative of excess nutrients. Chlorophyll a was measured consistently during the 2020 and 2021 monitoring seasons at all three stations. Chlorophyll a values are plotted in Figures 20 and 21, respectively for the three monitoring stations.

Figure 20: Chlorophyll a concentration for 2020 from the mid-lake, Mokins Bay and O'Rourke Bay Stations.

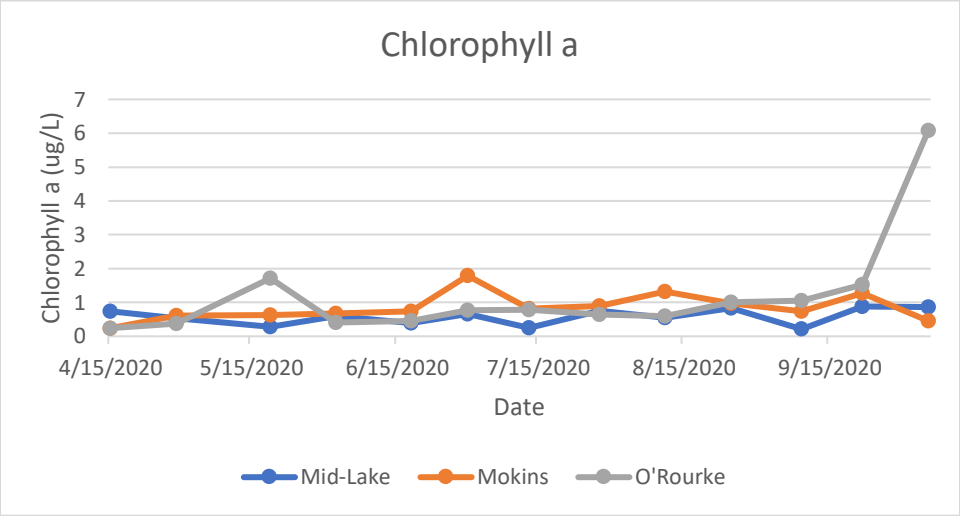


Table 10: Chlorophyll a data statistics (ug/L) 2021

Station	Average	Maximum	Minimum
Mid-Lake	0.579	0.88	0.21
Mokins Bay	0.856	1.79	0.24
O'Rourke Bay	1.205	6.08	0.24

Detection: 0.1 ug/L; half detection recorded for no detection

Figure 20: Chlorophyll a concentration for 2020 from the mid-lake, Mokins Bay and O'Rourke Bay Stations.

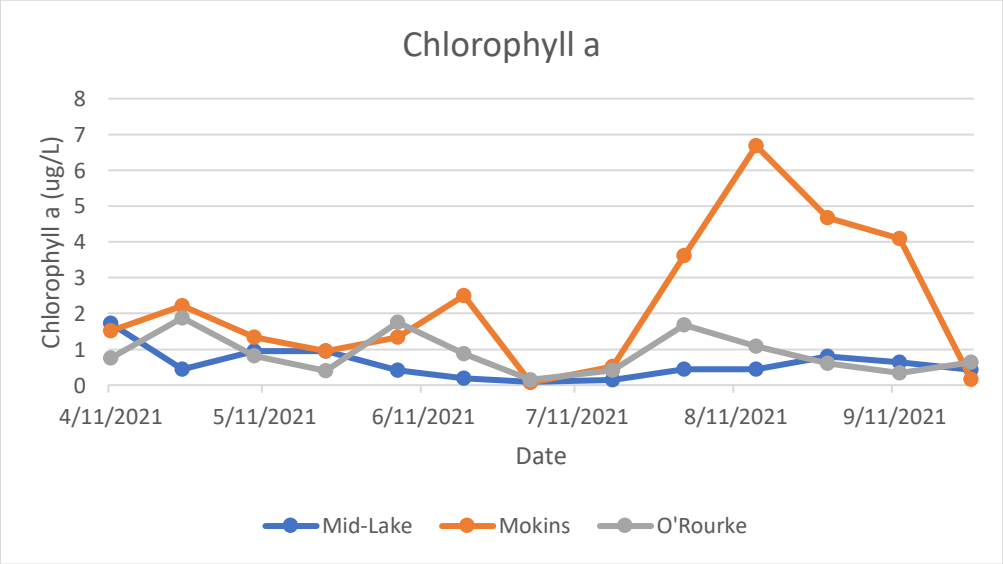


Table 11: Chlorophyll a data statistics (ug/L) 2021

Station	Average	Maximum	Minimum
Mid-Lake	0.588	1.72	0.09
Mokins Bay	2.282	6.68	0.07
O'Rourke Bay	0.876	1.88	0.15

Detection: 0.1 ug/L; half detection recorded for no detection

Chlorophyll a concentration was consistently below a microgram per liter at the mid-lake station during 2020. The Mokins Bay and O'Rourke Bay stations tracked slightly higher but similar during the 2020 monitoring season. The divergence from this pattern in the last O'Rourke Bay sample may be an error or contamination. Mid-lake chlorophyll a concentration again averaged well below one microgram per liter, but the variance was greater with a maximum of 1.7 microgram per liter. Again, the O'Rourke Bay chlorophyll concentrations reflected the 2020 measurements during 2021, but Mokins Bay provided consistently higher chlorophyll a concentration later in the 2021 monitoring season.

The Phytoplankton and Chlorophyll a Report for 2021 (Appendix B) provides the identical chlorophyll a data including the unusual increase in Mokins Bay late in the latter weeks of the summer

The chlorophyll a results suggest that both Mokins and O'Rourke Bay water are more like the mid-lake waters than those of the northern arm. However, this pattern is broken in the latter half of the 2021 monitoring season in Mokins Bay. Late in the season productivity as assessed by chlorophyll a content increased dramatically in Mokins Bay in the latter half of the 2021 monitoring season. The increase in productivity occurs in response to phosphorous concentration increase just as the water shallows and then large parts of Mokins Slough dewater.

Total Dissolved Solids:

Total dissolved solids measurement is an indicator of the overall biological activity in the lakes water column. Except for a very few values, the total dissolved solids were low typical of a low productivity lake. Total dissolved solids values were quite similar at the three stations in both 2020 and 2021. The values are most similar in 2020 with a bit more variance in 2021. Much of the 2021 variance was introduced by Mokins Bay samples again late in the monitoring season.

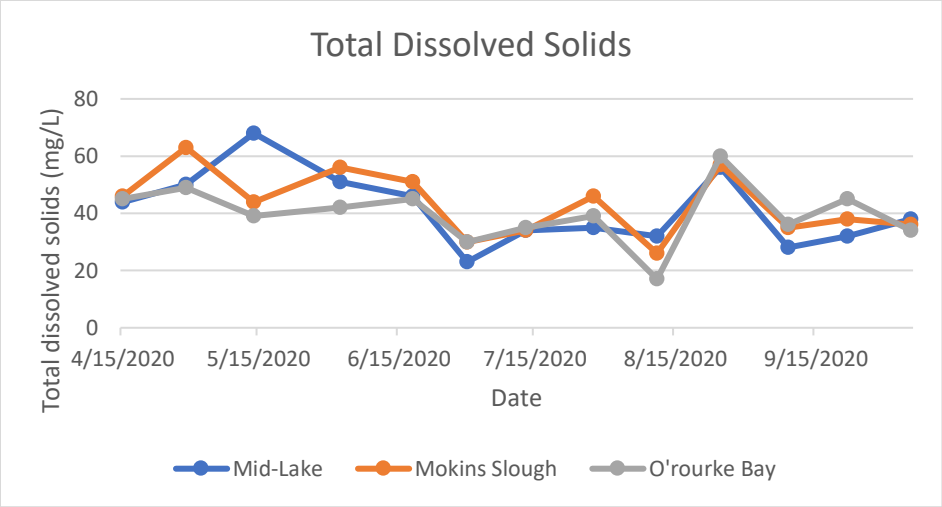


Table 12: Total dissolved solids data statistics (mg/L) 2020

Station	Average	Maximum	Minimum
Mid-Lake	41	68	23
Mokins Bay	43	63	26
O'Rourke Bay	40	60	17

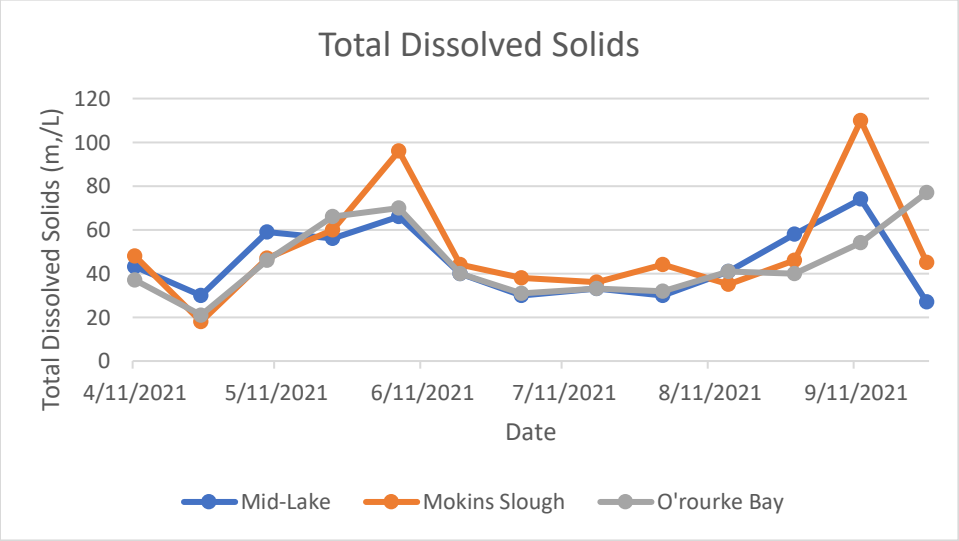


Table 13: Total dissolved solids data statistics (mg/L) 2021

Station	Average	Maximum	Minimum
Mid-Lake	45	74	27
Mokins Bay	51	110	18
O'Rourke Bay	45	77	21

Phytoplankton

The Phytoplankton results are contained in the Phytoplankton and Chlorophyll a Report for the 2021 (Appendix B) developed by Darren Brandt. The results are summarized in this section.

Phytoplankton is measured by two parameters density and biovolume. As has been established in previous reports blue green algae or cyanobacteria are the most numerous groups of species found in the lake at all stations. These species compose between a third to well over three-quarters of the algae individuals found in the lake dependent on the time of year. During the spring months diatoms and flagellated algae together comprise the other two thirds of the individuals, while as the season progresses, the cyanobacteria come to dominate cell numbers (density). However, the cyanobacteria are very small in size as compared to the eukaryotic algae. A cyanobacteria might be compared in size to a motorboat as compared to a eukaryotic alga (diatoms, flagellates, dinoflagellates and greens) which on the same scale would be aircraft carriers or at least cruisers. For this reason, when biovolume is measured, the eukaryotic algal species dominate. Biovolume results for the 2021 monitoring season provided a pattern of diatoms dominating early in the season at all stations with flagellates and green algae increasing as the water warms with the progressing season. Similar patterns have been observed for the mid-lake in past seasons. The pattern for Mokins and O'Rourke bays were similar, however, flagellated algal forms peaked in volume in early summer in Mokins Bay and a bit later in O'Rourke Bay. Since the 2020 results were unreported it is difficult to ascribe any significance to these result.

Blue green algae or cyanobacteria increase in density at all three monitoring sites as the 2021 season progressed. This is a typical pattern likely caused by the depletion of nitrogen chemical species in the water column as that nitrogen is progressively incorporated into biomass. However, the blue green algae increase to twenty-five to fifty percent greater density at the Mokins Bay station in the later summer months. This increase cyanobacteria density is associated with the increase in total and ortho phosphorous and chlorophyll a in Mokins Bay.

Discussion:

Mid-lake monitoring during 2020 and 2021 re-enforce the most recent 2019 results demonstrating the core of Hayden Lake is a clear oligotrophic water body. The general good health of the core of the lake is best reflected in the dissolved oxygen results (figure 8 &9). When the lake was at its peak of thermal stratification, dissolved oxygen increases with depth. A lake which has too much productivity due to plant growth nutrient issues, would exhibit a dissolved oxygen "sag"; dissolved oxygen would decrease with depth. Total and ortho-phosphate measurements support the Hayden Lake's low nutrient status. Total Phosphorous average 4 and 5 micrograms per liter respectively in 2020 and 2021. The thirty-year average for total phosphorous at the mid-lake station is 7.5 micrograms per liter, well above the averages observed in the two years of mid-lake station monitoring. All the total phosphorous measurements were well withing the oligotrophic range; less than ten micrograms per liter. Ortho-phosphate concentrations at the mid-lake station are undetectable or at best the one microgram per liter detection limit. Even though the phosphorous levels are well within the range where the nutrient limits plant growth, nitrogen chemical species are at expected levels. Ammonia does appear in the lake at low concentrations, possibly when algal blooms collapse and certainly after herbicides are applied

over broad areas. Chlorophyll a measurement and calculated organic nitrogen used as a surrogate for productivity indicate the low productivity of the general lake's waters.

Both Mokins and O'Rourke Bays are fed by streams Mokins and Yellowbanks, respectively that drain from entirely forested watersheds. Two years of monitoring at stations in Mokins and O'Rourke Bays indicate their waters are more akin to the main body of the lake, as compared to the lake's northern arm. Although slightly higher, total and ortho-phosphorous are in the range of oligotrophy. Nitrogen chemical species are in expected low ranges. Ammonia does appear late in the both seasons in Mokins Bay and in 2021 in O'Rourke Bay after ProcellaCOR herbicide treatment. Both chlorophyll a and organic nitrogen measures of productivity demonstrate that it was low during monitoring year 2020. However, the situation in Mokins Bay shifted dramatically during the second half of monitoring season 2021. Low water levels progressively exposed lake bottom in Mokins Slough. As this unusual low water event progressed, higher total phosphorous and consequently ortho-phosphorous concentrations were observed. Productivity increased in the second half of the 2021 monitoring season as observed from chlorophyll a and higher organic nitrogen. Phytoplankton observations add additional evidence for increased productivity. Cyanobacteria numbers increased twenty-five to fifty percent greater at the Mokins Bay station as water levels progressively fell and more lake bottom was exposed. Biovolume impacts were not that significant, because the cyanobacteria are relatively small as compared to the eukaryotic algae. O'Rourke Bay showed some tendency towards higher nutrients and productivity, but was muted likely because the bay did not dewater at its head.

Conclusions & Recommendations:

The results of the two years of monitoring confirm the oligotrophic nature of Hayden Lake and that no buildup of excess organic material is indicated. Mokins Bay and O'Rourke Bay waters are more akin to the main body of Hayden Lake. Some water quality parameters are a bit higher, but not significantly so. However, the low lake level situation encountered during the second half of the 2021 monitoring season caused large areas of Mokins Slough to dewater. As this occurred plant growth nutrient levels generally rose as did algal productivity. Likely nutrients, especially ortho-phosphorous were released from shallow or exposed lake sediments increasing algal productivity, primarily cyanobacteria, in Mokins Bay. The results suggest that declining lake levels could have an adverse impact on the lake's water quality at least locally.

Based on the results, the following is recommended:

: Obtain a technical memorandum on the Monitoring Year 2020 chlorophyll a and phytoplankton results from Advanced Eco-Solutions to verify by comparison the impact of late season 2021 low water on productivity in Mokins Bay.

: Mid-lake water quality monitoring be sustained until lake water levels return to normal;

: Monitoring be continued on Mokins Bay while water levels remain low;

: Bervin and Windy Bays (possibly Cramps) be monitored as the last deep bays of the lake, for which a water quality record should be developed.

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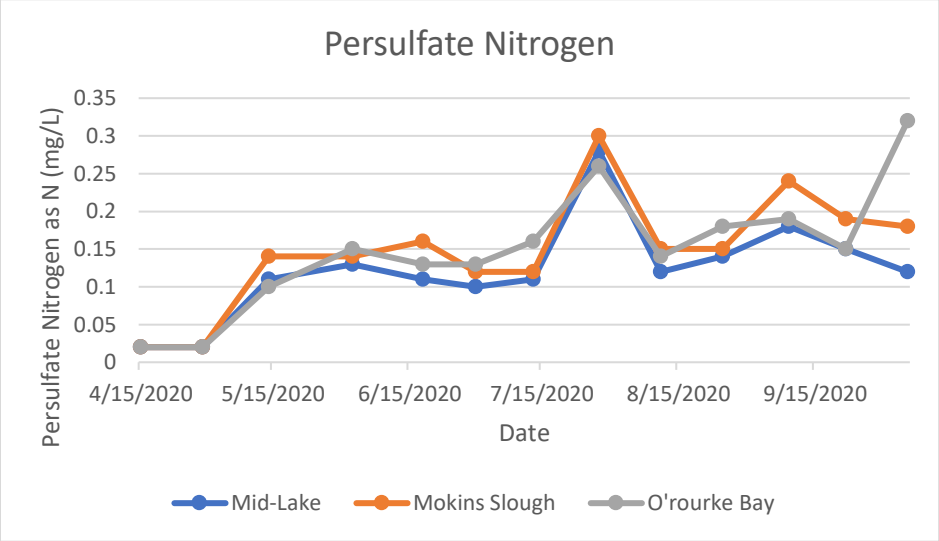
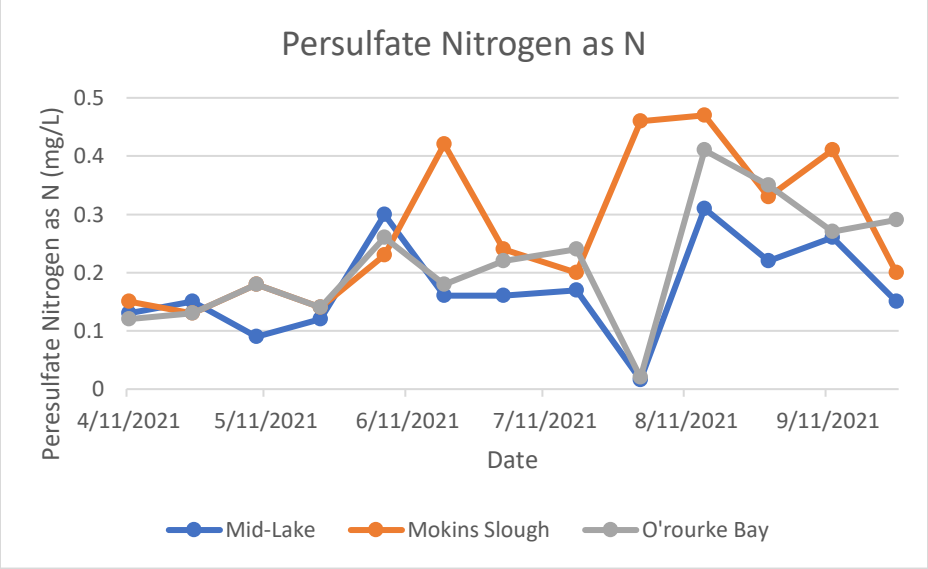
Utermohl, H. 1958. Zur Vervollkommnung der Quantitativen Phytoplankton Methodik. Int. Verein. theor. angew. Limnologie, Mitteilung 9

Appendix A:



Persulfate nitrogen data statistics (mg/L) 2020

Station	Average	Maximum	Minimum
Mid-Lake	0.12	0.28	0.02
Mokins Bay	0.15	0.30	0.02
O'Rourke Bay	0.15	0.32	0.02



Persulfate nitrogen data statistics (mg/L) 2020

Station	Average	Maximum	Minimum
Mid-Lake	0.17	0.31	0.02
Mokins Bay	0.27	0.47	0.13
O'Rourke Bay	0.22	0.41	0.02

Appendix B: Phytoplankton and Chl a Report 2021 by Darren Brandt of Advanced Eco-Solutions dated April 29, 2022