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March 12th, 2024

TO: Highland Lake Watershed Association
ATTN: Candy Perez
FROM: Kendra Kilson, Research Scientist and George Knoecklein, PhD
Re: Highland Lake 2023 Water Quality Results

Discussion of 2023 Water Quality Results

This summary letter presents the results of 2023 Highland Lake water quality monitoring, including water clarity, dissolved oxygen profiles and water temperature profiles, plankton samples, and nutrient chemistry. These data were collected from three stations located in the deepest water of the three large bays, North Bay, Center Bay, and South Bay. HLWA Volunteers visited the three stations monthly from May to October, NEAR visited the three stations in April and November. Nutrient chemistry included total phosphorus and total nitrogen from three depths at each station.

Water Clarity

The water clarity goal for Highland Lake is for all stations to experience at least two months when the Secchi disk depth is at least 4 meters (**Table 1**). In 2023, water clarity was the best in April, with all stations having readings of 4.5m or better. Clarity decreased slightly by May, but all stations continued to have clarity readings of >4m. Clarity decreased again by June, but all stations retained Secchi disk measurements of >4m. Water clarity readings in May and June ranged between 4.15 and 4.5m. Water clarity declined in July to the lowest seasonal readings of ~3.5m at all three stations. Heavy rains, that were pretty much continuous all summer, likely contributed significantly to the poor clarity in July, as well as in August, when clarity was only slightly improved. Water clarity in July and August ranged from 3.4 to 3.8 meters, with very little difference between stations. Clarity improved notably in September, with all stations reporting clarity readings >4m, but declined in October and again in November, such that poorest readings for the season occurred that month, when Secchi depth was 2.3-3.0 meters.

Overall, water clarity did not vary significantly between stations, with a couple of interesting exceptions: a low September value in North Bay when other stations had notably better clarity, in October Middle Bay had much better clarity than either North Bay or South Bay, and in November the South Bay clarity was notably worse than North Bay and Center Bay.

Table 1. 2023 Secchi disk depths (meters) at each station.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
North Bay	4.7	4.5	4.2	3.4	3.8	4.0	3.1	3.0
Middle Bay	5.0	4.3	4.3	3.6	*	4.8	4.3	3.3
South Bay	4.5	4.3	4.15	*	3.4	4.8	3.7	2.3
Lake Average	*4.7*	*4.4*	*4.2*	*3.5*	*3.6*	*4.5*	*3.7*	*2.9*
Difference Between Stations	*0.5*	*0.2*	*0.1*	*0.2*	*0.4*	*0.8*	*1.2*	*1*

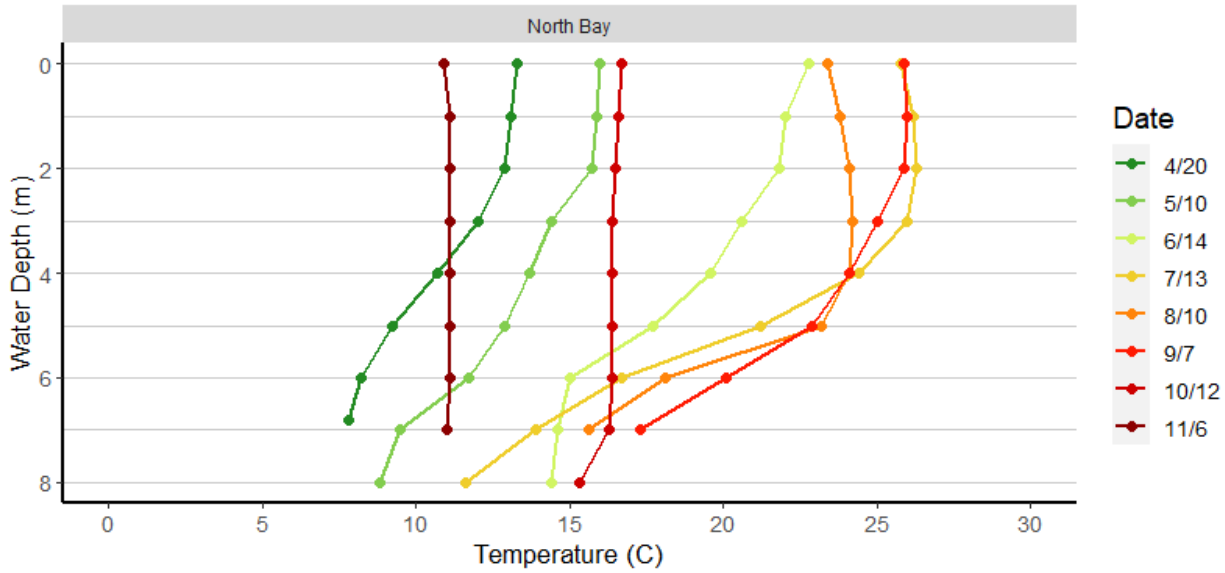
** = measured but not recorded*

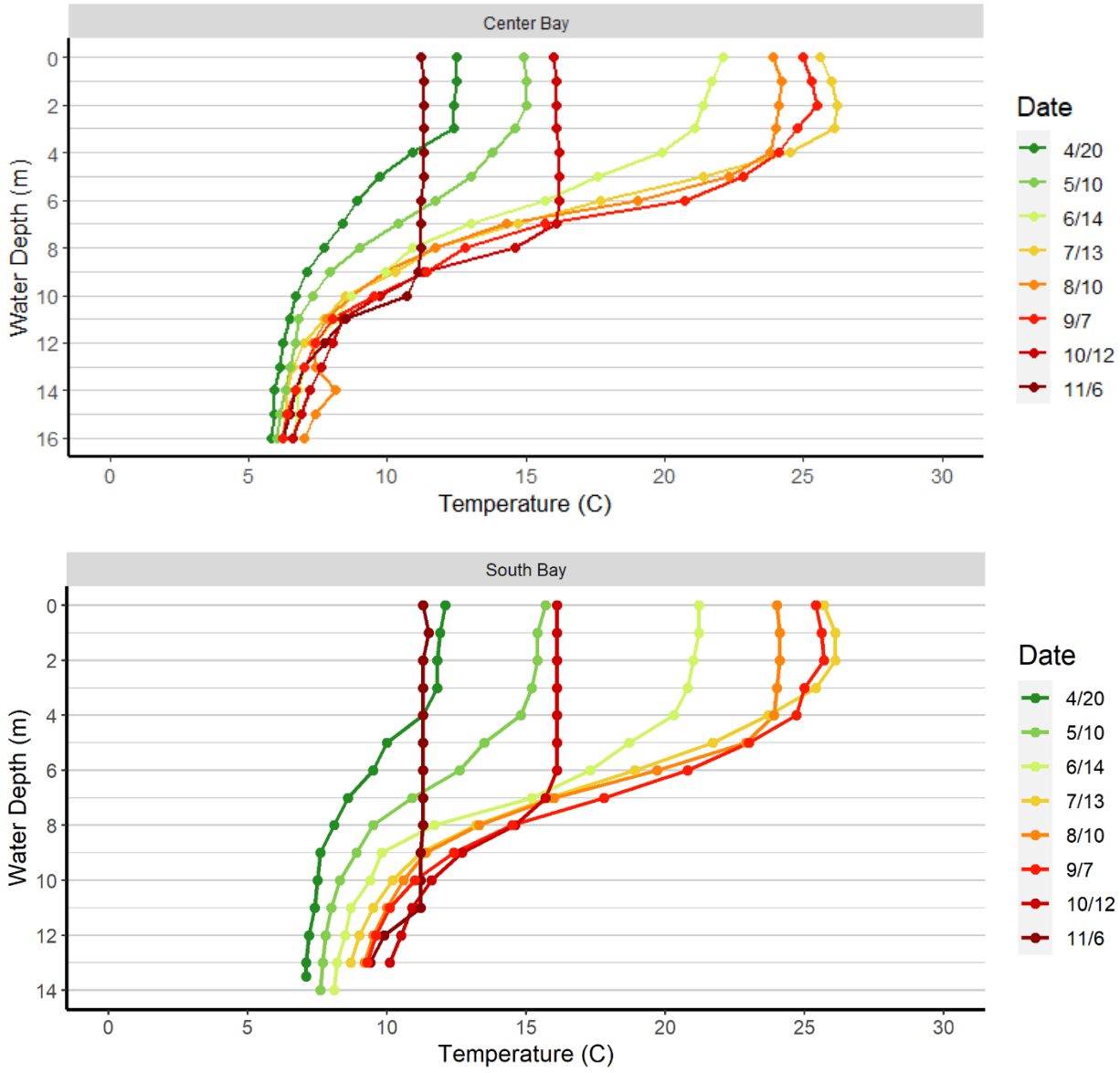
Water Temperature

Lake water temperature is typically near 4°C in early spring, after ice melt. The water temperature increases at the surface in May and June, such that upper water is warmer than bottom water. This process continues at all stations until late August or early September, after which surface and upper water temperature decreases until equal to bottom temperature.

In 2023, the first profile in April shows that the lake had already gained heat, ~12°C at the surface and ~7°C at the bottom, so the water column was no longer isothermal (**Figure 1**). A critical aspect of the first sampling is that the water column is equal at all depths. The water in the upper 7 meters warmed quickly in May in June and stayed warm through August and into September. Typically, the date of warmest surface water temperatures is August 1st, indicating that the lake was at maximum temperature for a month rather than a couple of days. The lake was not fully mixed to the bottom in Middle Bay or South Bay on the date of the last profile Nov 6th.

Figure 1. Temperature profiles at North, Center, and South Bays in 2023.

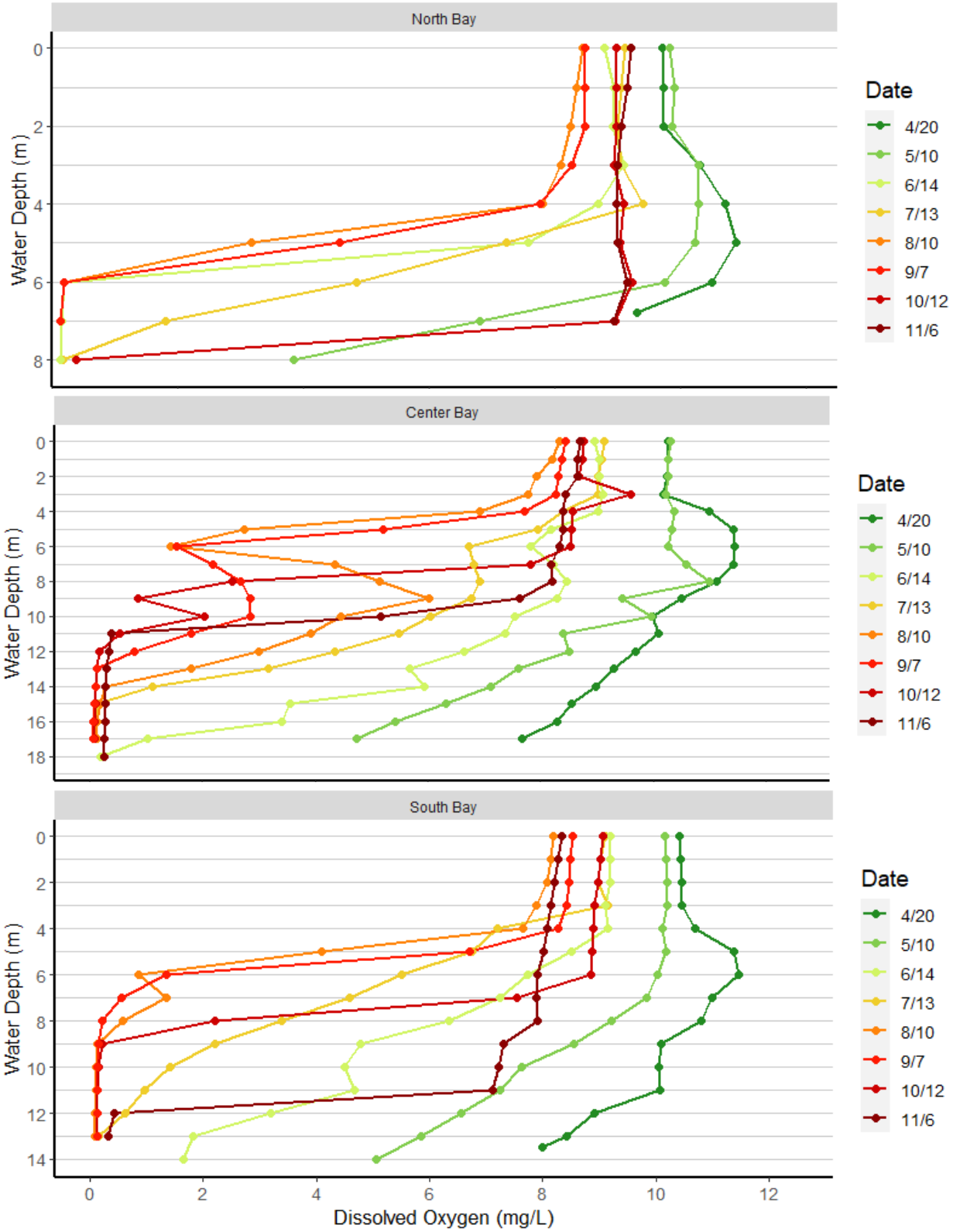




Dissolved Oxygen

Dissolved oxygen in lake water tends to be fully saturated throughout the whole water column in the spring and fall months but only surface waters in the summer. The surface water is the layer of water on the surface of a lake that shares the same warm temperature, which in Highland Lake tends to be around 4 meters in June and July but gets deeper in August and September (**Figure 2**). Dissolved oxygen behaves sporadically in the middle depths of Center Bay, where instead of a smooth decline in concentration with depth, some depths had either higher or lower values than water above or below. For example, in August, dissolved oxygen at 6m was 1.2 mg/L, but at 7m dissolved oxygen was 4.2mg/L and 6 mg/L at 9m. By July, the water at the bottom of each station was anoxic.

Figure 2. Dissolved oxygen profiles at North, Center, and South Bays in 2023.



Bottom Water Anoxia

As detailed in the 'Highland Lake 2020 Water Quality Report & Long-Term Data Assessment', dissolved oxygen below 1 mg/L (termed 'anoxic') should not occur above **4 meters** below the surface at North Bay, **9 meters** below the surface at Center Bay, and **8 meters** below the surface at South Bay.

In North Bay, dissolved oxygen was present in all waters to the bottom only in April and May (**Table 2**). By mid-June, the bottom two meters of water were anoxic. Interestingly, in July, the anoxic boundary decreased to a half meter from the lake bottom. By August, the anoxic boundary had increased close to the level observed in June.

The bottom water was also oxygenated in April and May in Center Bay. The bottom water was anoxic by mid-June and the anoxic boundary continued to increase until reaching a maximum height of 8.9 meters in October. By November, the anoxic boundary had decreased 2 meters from its October level, but there were still seven meters of anoxic water, which is concerning.

At South Bay, the bottom water remained oxygenated through June. By July, the bottom five meters of water were anoxic, and though the anoxic boundary declined between July and November, the bottom meter of water was still anoxic in November.

Table 2. 2023 anoxic boundary depths (meters below the surface)

		Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
North Bay	2023	bottom	bottom	5.9	7.5	5.7	5.8	7.9	bottom
	Comparison to 4m Anoxic Boundary Threshold			>4	>4	>4	>4	>4	
Center Bay	2023	bottom	bottom	17.0	14.1	13.5	11.8	8.9	10.9
	Comparison to 9m Anoxic Boundary Threshold			>9	>9	>9	<9	<9	>9
South Bay	2023	bottom	bottom	bottom	10.9	6.0	6.4	8.6	11.9
	Comparison to 8m Anoxic Boundary Threshold				>8	<8	<8	>8	>8

Nutrients

Total Phosphorus

Surface-water total phosphorus (TP) thresholds have been established for the season and for each month using the long-term data set. Measured TP concentrations in Highland Lake in any one month should remain near or below that month's long-term average, and the seasonal average should be equal to or below the long-term average.

In 2023, surface-water TP was elevated above the lake-wide long-term average at all stations in May and August, in Center Bay in September, and in North Bay and South Bay in October (**Table 3**). The 2023

average for the three stations was at or below the long-term mean. While TP concentrations were above goal levels in several months, 2023 showed improvement compared to 2022, when surface-water TP was elevated above the long-term mean at all stations in most months, and the 2022 seasonal average was higher than the long-term average for all three stations.

TP in the bottom water in North Bay remained relatively low throughout the season, reaching a maximum concentration of 17 ppb in August (**Table 4**). In Center Bay, however, bottom water TP concentration was elevated, reaching a maximum concentration of 183 ppb in November. As discussed in the Dissolved Oxygen section above, there were still 7 meters of anoxic water at the bottom of the lake on the November sampling date, meaning internal loading of nutrients likely continued well past this last sampling date.

In South Bay, TP in the bottom water reached a maximum concentration of 53 ppb in October. TP remained elevated in November but had decreased from the October level, as the anoxic boundary had dropped to one meter above the lake bottom.

Table 3. 2023 surface-water (1m) total phosphorus concentrations (ppb) and monthly lake-wide average surface TP water concentrations.

	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Average
North Bay 2023	9	12	7	9	11	7	13	11	10
Center Bay 2023	11	15	6	8	11	19	10	9	11
South Bay 2023	6	15	5	10	15	1	14	10	10
Average of all Bays	9	14	6	9	12	9	12	10	11

Table 4. 2023 bottom-water total phosphorus concentrations (ppb).

	Apr-20	May-10	Jun-14	Jul-13	Aug-10	Sep-7	Oct-12	Nov-6	Average
North Bay	12	15	11	11	17	9	13	10	12
Center Bay	6	12	4	15	17	27	78	183	43
South Bay	3	10	6	10	13	22	53	31	19

Total Nitrogen

The upper tolerable level for total nitrogen in surface-waters of Highland Lake is 250ppb. TN was elevated above this threshold in North Bay in May, June and July (**Table 5**). In Center Bay, TN was elevated above this threshold in May, August and September. The September 7th concentration of 596ppb was particularly high. In South Bay, TN was elevated above this threshold in August, October and November.

TN in the bottom water was particularly elevated in Center Bay in September, October, and November, and in South Bay in October and November (**Table 6**).

Table 5. 2023 surface-water (1m) total nitrogen concentrations (ppb).

	Apr-20	May-10	Jun-14	Jul-13	Aug-10	Sep-7	Oct-12	Nov-6
North Bay	233	267	264	268	230	243	247	243
Center Bay	244	267	184	225	273	596	222	211
South Bay	201	233	212	220	354	229	266	272

Table 6. 2023 bottom-water total nitrogen concentrations (ppb).

	Apr-20	May-10	Jun-14	Jul-13	Aug-10	Sep-7	Oct-12	Nov-6
North Bay	243	234	203	196	245	298	239	239
Center Bay	223	288	277	318	560	992	785	1,677
South Bay	190	263	289	288	382	546	678	800

Ammonia Nitrogen

Typically, in well-oxygenated waters, ammonia nitrogen (NH_3) is at very low concentrations or below detection. Ammonia is rapidly released from bottom sediments when overlain with anoxic water. The longer the anoxia persists, the higher the rate of ammonia release such that most if not all the total nitrogen in the bottom water is ammonia. Ammonia-nitrogen concentrations at the bottom of the lake ranged from <3ppb to 1,344ppb across the three stations in 2023 (**Table 7**). Bottom water at Center Bay showed a slow steady increase in ammonia between April and July, followed by a rapid increase during August, September, and October, and a dramatic increase in November. This indicates that bottom sediments at Center Bay were internally loading materials into overlaying water in November, when the anoxic boundary was located at the same depth as the thermocline.

Table 7. 2023 bottom-water ammonia nitrogen concentrations (ppb).

	Apr-20	May-10	Jun-14	Jul-13	Aug-10	Sep-7	Oct-12	Nov-6
North Bay	7	9	44	11	5	ND*	16	4
Center Bay	43	92	106	105	293	397	543	1,344
South Bay	9	70	95	170	156	185	358	511

**ND=Non-Detect, sample below 3ppb detection limit.*

Chloride

Chloride data was collected from the three bays in April and October 2023, with results in **Table 8**. The values of 36± mg/L in April shows essentially equal concentrations lake wide. We measure chloride very rarely because it is not involved in the eutrophication process. In October, chloride was 30% lower than April levels at all three stations.

Table 8. 2023 surface-water (1m) chloride concentrations (mg/L).

	Apr-20	Oct-12
North Bay	37.0	25.9
Center Bay	36.8	25.4
South Bay	35.9	23.4

Phytoplankton

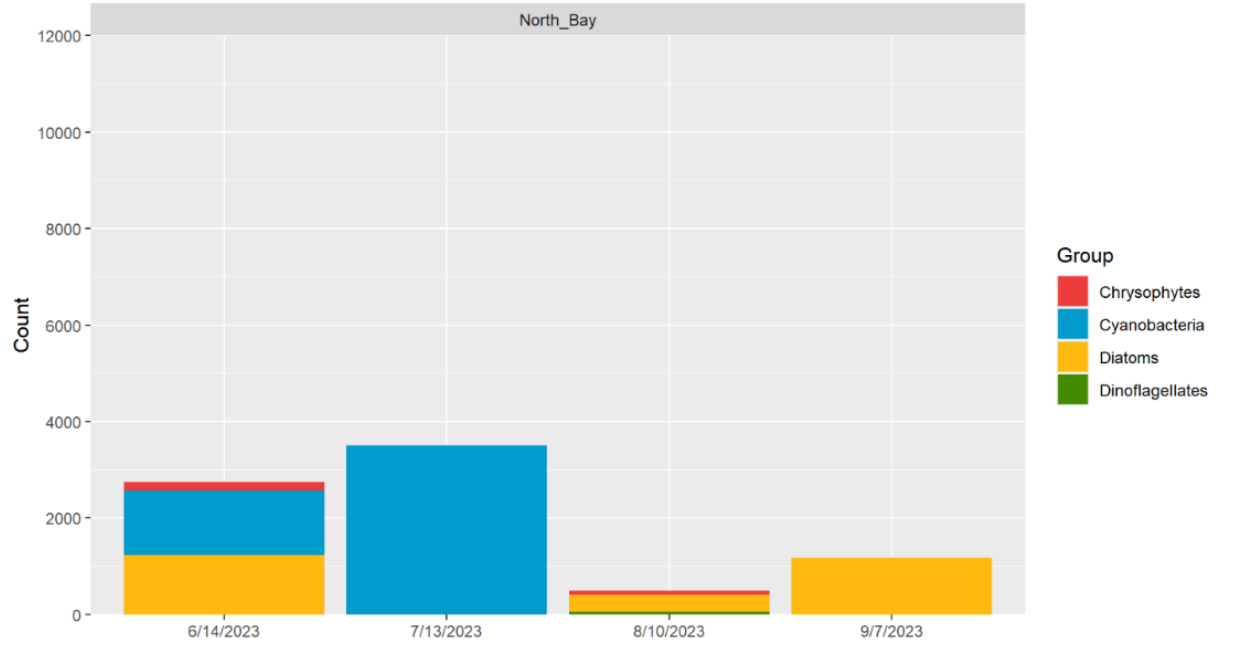
Phytoplankton samples were collected at all three monitoring stations from June through September. In April, May, October, and November, phytoplankton samples were collected only at Center Bay.

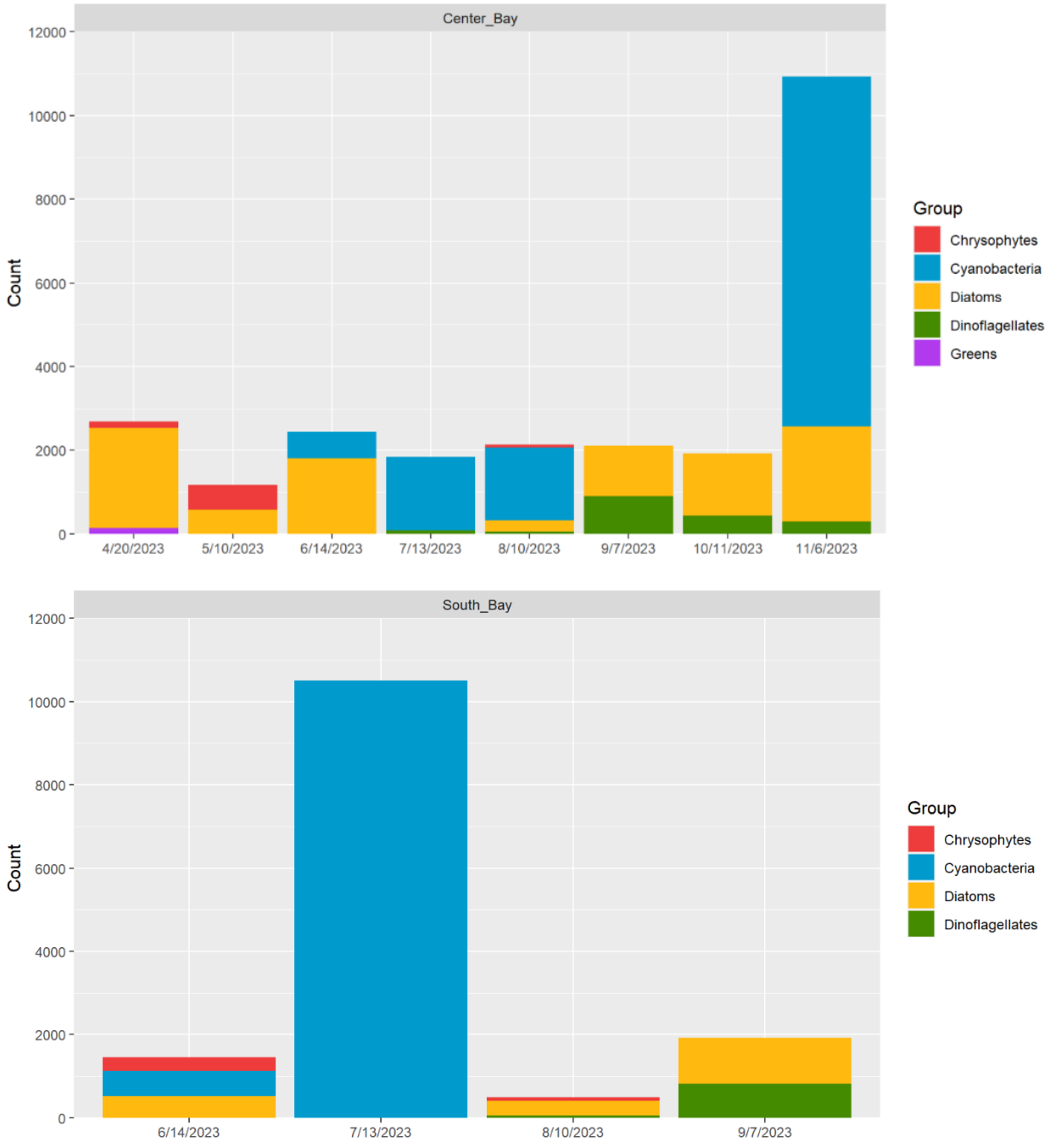
Phytoplankton presence was generally low throughout the lake in 2023 (**Figure 3**). However, each bay experienced dominance of Cyanobacteria in July, although numbers were low (highest in South Bay). North Bay was dominated by Cyanobacteria and Diatoms, though both remained at relatively low levels.

Total phytoplankton presence in Center Bay was dominated by diatoms in April through June at moderate numbers. These were replaced by cyanobacteria in July and August, but numbers were low at 1,000 to 3,000 cells/mL. Diatoms returned in August and remained in the water column for the remainder of the season. There was an increase in cyanobacteria in November, but numbers were still considered low at ~8,400 cells/mL (**Table 10**).

In South Bay, total phytoplankton numbers remained below 2,000 cells/mL during the June, August, and September sampling events. Cyanobacteria was the only phytoplankton group observed in July. Again, though numbers exceeded 10,000 cells/mL, this is considered low with regard to relatively probability of health effects.

Figure 3. Phytoplankton counts at North, Center, and South Bays in 2023.




Center_Bay
Count
12000
10000
8000
6000
4000
2000
0
4/20/2023
5/10/2023
6/14/2023
7/13/2023
8/10/2023
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Group
Chrysophytes
Cyanobacteria
Diatoms
Dinoflagellates
Greens
South_Bay
Count
12000
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6/14/2023
7/13/2023
8/10/2023
9/7/2023
Group
Chrysophytes
Cyanobacteria
Diatoms
Dinoflagellates

Table 4. WHO guidance values for the relative probability of health effects resulting from exposure to cyanobacteria.

Relative Probability of Acute Health Effects	Cyanobacteria Density (Cells/mL)
Low	< 20,000
Moderate	20,000-100,000
High	100,000-10,000,000
Very High	> 10,000,000

Zooplankton

Zooplankton samples were collected from Center Bay every month from April through November. The most abundant group of zooplankton were rotifers (**Figure 4**). Rotifers dominated in most months. Rotifer populations increased after July but remained below 7.5 animals per liter. Calanoids were present only in June at low populations (<1 animal per liter). Cyclopoids were present in every month except July, with high numbers of small-bodied forms, <0.4mm (**Figure 5**). There were also high numbers of small-bodied Cladocera in most months, except for September.

Figure 4. Zooplankton counts at Center Bay in 2023.

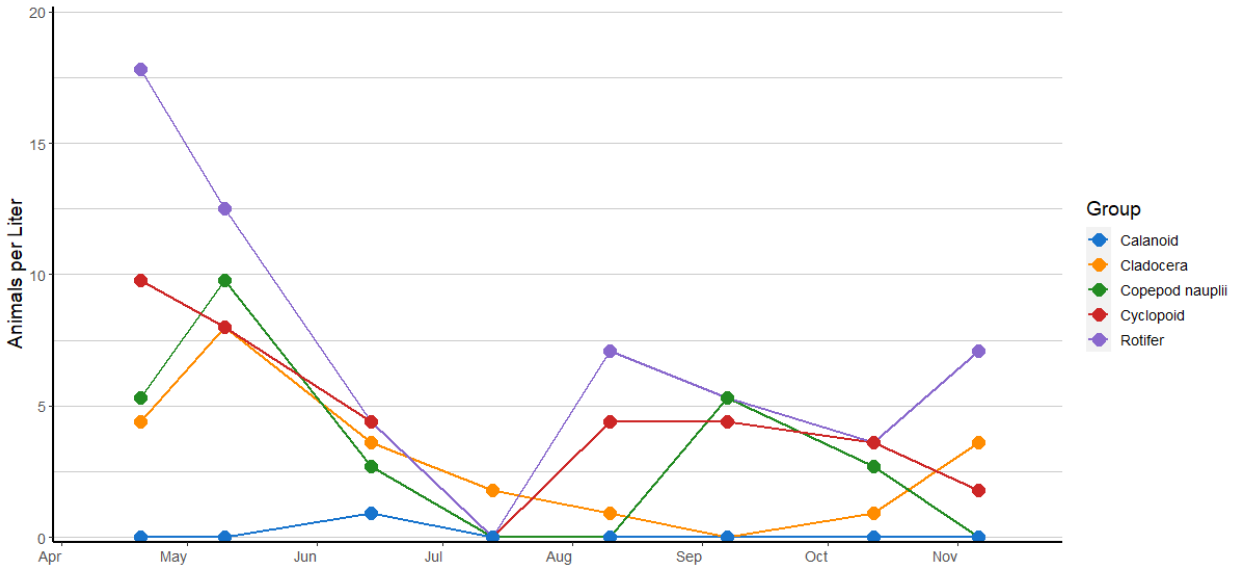
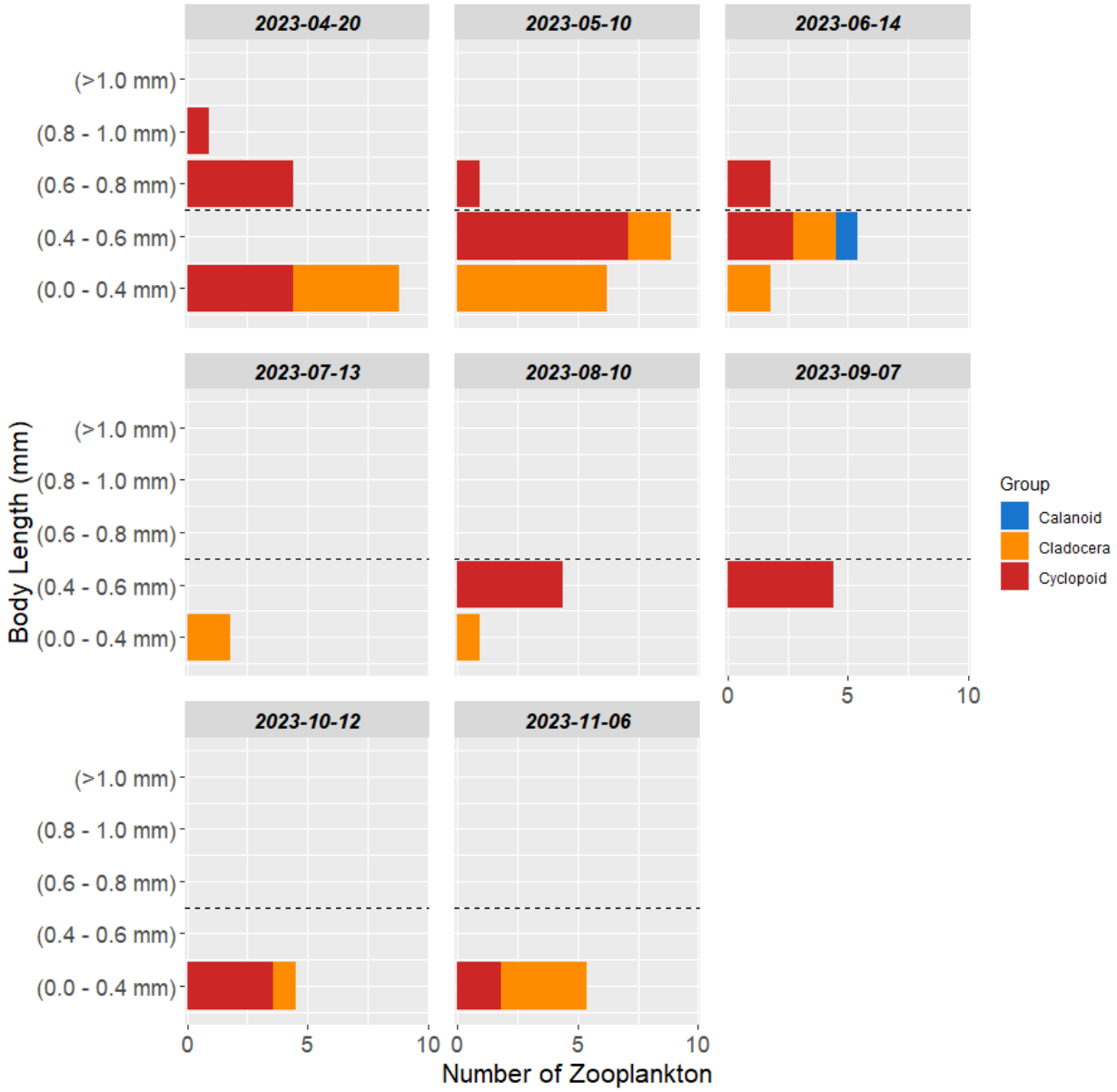


Figure 5. Zooplankton body lengths at Center Bay in 2023.



Recommendations

- The existing water quality monitoring program has been extremely successful and should be continued. Due to climate change, the sampling season now begins in March and ends in December, indicating that lake monitoring should include March and December visits. March is the new April when the lake has isothermal conditions, and December is suggested because on the last monitoring visit, November 6th, the lake was not isothermal in Center Bay and anoxia persisted from 11m to the bottom at 18m. One of the goals of the last sampling is to catch the lake when there is no stratification, and the bottom water is fully oxygenated.
    - An alternative is to deploy remote dissolved oxygen sensors in the deep water of each bay and collect continuous data.
- The Town and HLWA should continue efforts to reduce nutrient loading from the watershed, as detailed in the 'Highland Lake 2020 Water Quality Report & Long-Term Data Assessment'.
    - If chloride concentration is a concern to the HLWA, the inlet streams should be sampled to determine the baseline chloride concentration coming in from the watershed. This could be done once in the spring –prior to May 1st, by collecting samples from all the inlets around the lake on the lakeside of the road. The data appear to show chloride concentration decreased over the course of the season.
    - The long-term conductivity data set from lake measurements can be examined for any trends as part of our 2024 annual report. This analysis will consist of seasonal changes in conductivity, differences between basins, and the long-term variability, if any.
- Internal loading of phosphorus at the bottom of Center Bay and South Bay is elevated in September and October. Ammonia data show internal loading begins in July and intensifies through November.
    - An examination of all the phosphorus data is suggested to be included in the 2024 annual report. This analysis would consist of estimating the phosphorus loading rate and determining whether loading to upper water is occurring.

Highland Lake water quality sampling stations.