Church Lake Water Quality Assessment

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Prepared for:
Church Lake Association

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Introduction

Water quality issues are of concern to homeowners residing on Church Lake. Two particular concerns are salt accumulation and high phosphorus (P) concentrations in the lake's hypolimnion (bottom layer). A study conducted in 2019 (Progressive AE 2019) revealed concentrations of total phosphorus (TP) at ~4,000 to 5,000 µg/L (equivalent to parts per billion: ppb) and chloride (Cl^-) atf 350 to 370 mg/L (equivalent to parts per million: ppm) in the bottom waters of Church Lake. These TP concentrations vastly exceed the recommended TP levels for Michigan lakes of 25 to 30 ppb. Typical Cl^- concentrations in natural surface freshwater systems are less than 20 mg/L although Cl^- pollution from road salt runoff can reach 13,500 mg/L (Hintz and Relyea 2019). The U.S. Environmental Protection Agency (1988) lists acute and chronic freshwater aquatic life water quality criteria for Cl^- of 860 and 230 mg/L, respectively (Canada is 160 mg/L), but studies have shown that biological impacts can occur at concentrations lower than those thresholds (Hintz and Relyea 2019).

The ecological consequences of high TP and Cl^- concentrations are significant. High phosphorus concentrations are correlated with algal blooms, usually cyanobacteria (blue-green algae), which can produce toxins and form surface scums. When these algae die, they settle to the lake bottom where they decompose; this process consumes dissolved oxygen and thus lake bottoms can become hypoxic (< 1 mg/L dissolved oxygen) or anoxic (< 0.1 mg/L dissolved oxygen), impacting aquatic organisms that require oxygen. High Cl^- concentrations also can impact freshwater biota that are not accustomed to salt levels, resulting in reductions in growth, reproduction, and even death in extreme situations.

Road salt, usually applied as sodium chloride (NaCl), is denser than water and sinks to the lake bottom. As it dissolves, a chemical gradient is established in lakes (less salt in the upper layer, more salt in the bottom layer). Most Michigan lakes develop a thermal gradient in summer (warmer in the upper layer, colder in the bottom layer); this thermal gradient breaks down each spring and fall as the temperature throughout the water column becomes uniform, resulting in lake turnover and mixing. However, a salt gradient remains in place throughout the year, preventing the lake from turning over; in this case, the dissolved oxygen in the upper layer cannot reach the bottom waters, so not only is there a lack of oxygen at the bottom but also the phosphorus that accumulates in the bottom layer cannot reach the upper layers, where it would be reduced in concentration due to uptake by algae.

Grand Valley State University's Annis Water Resources Institute (AWRI) began a water quality monitoring initiative in Church Lake at the request of the Church Lake Homeowner's Association. The goal of this initial study was to investigate the relationship between TP and Cl^- in Church Lake over space and time for a year. This report details and summarizes the results of those monitoring efforts from August 2020 through August 2021.

Additional studies are being conducted by students in the Steinman lab at AWRI to better understand the P and Cl^- dynamics in the Church Lake system. Those data are not part of this study, as they were funded separately, but will be shared with the Homeowners Association as they become available.

Methods

Monitoring occurred twice monthly at the tributary draining into Church Lake from the East Beltline and once monthly at the deep site in the Lake. Occasional sampling of the outlet to Middleboro Lake also occurred. Surface water was collected in the lake via grab sample, and at every 3 m (~9.8 ft) by use of a Van Dorn water sampler. Church Lake samples were collected via kayak or rowboat for most of the year or by drilling a hole in the ice with an auger in the winter months. No lake samples were collected during January or March 2021 due to unsafe ice conditions. Sampling dates and locations are described in more detail in Fig. 1 and Tables 1 and 2.

Physicochemical parameters of water quality including temperature, dissolved oxygen (DO), pH, specific conductivity (SpCond), total dissolved solids (TDS), and turbidity were measured using a YSI 6600 sonde. At least 250 mL of site water was collected for total phosphorus (TP) analysis, from which two 20 mL subsamples were collected and syringe-filtered through acid-washed 0.45 µm nylon membrane filters into scintillation vials for analysis of Cl^- and soluble reactive phosphorus (SRP), which is the bioavailable form of phosphorus.

Water samples were stored on ice during transport to the laboratory. TP and SRP samples were refrigerated until measured on a SEAL AQ2 discrete auto-analyzer (USEPA 1993). Cl^- samples were frozen until measured on a Dionex ICS 2100 RFIC Chromatography system (Pfaff 1993). Any TP or SRP concentrations below their respective detection limits were calculated as ½ the detection limit (resulting in values of 3.5 or 2.5 µg/L, respectively) and any negative turbidity values were changed to 0 for data analysis.

Daily precipitation totals measured by a permanent weather station at the Gerald R. Ford International Airport in Grand Rapids, MI (GRR), which had 100% coverage across the sampling year, were downloaded from the National Oceanic and Atmospheric Administration's National Centers for Environmental Information (NCEI) Climate Data Online website (https://www.ncdc.noaa.gov/cdo-web/).

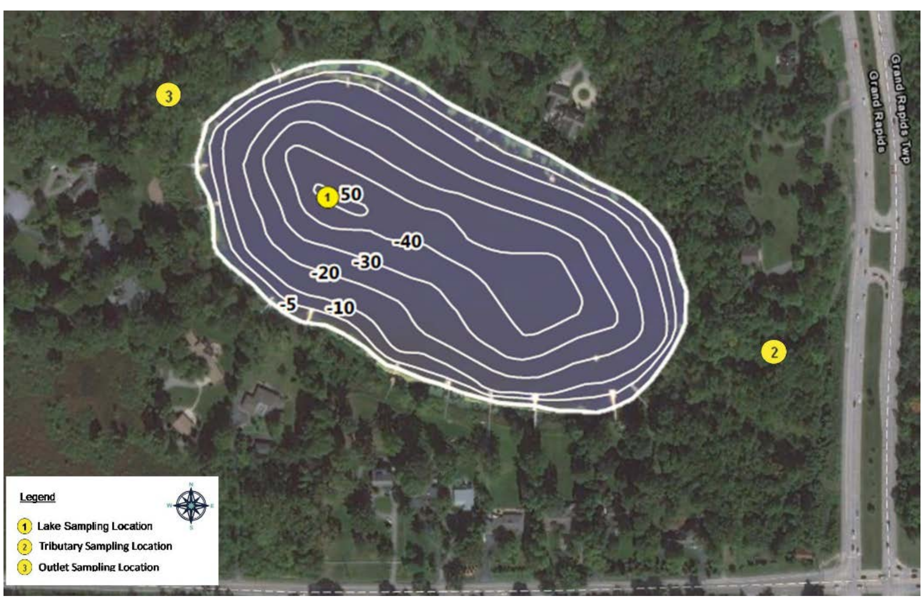

Figure 1. Map of Church Lake with monitoring sites indicated by yellow symbols. The legend describes the sites. Bathymetric lines indicate depth in feet from the lake surface to bottom sediment.

Table 1. Dates and locations of water quality monitoring in Church Lake and its upstream drainage tributary during base and storm flow sampling events in 2020-21. Monthly lake data could not be collected in January or March 2021 due to unsafe lake ice conditions.

Date	Lake	Tributary	Sampling Notes
8/3/2020	X	X	
8/21/2020		X	
9/1/2020	X	X	
9/16/2020		X	
10/5/2020	X	X	
10/13/2020		X	storm #1
10/19/2020		X	
11/5/2020	X	X	
11/19/2020		X	
12/3/2020	X	X	
12/18/2020		X	
1/8/2021		X	no January lake data
1/22/2021		X	
2/1/2021	X	X	
2/17/2021		X	
2/24/2021		X	snowmelt
3/8/2021		X	no March lake data
3/19/2021		X	
4/2/2021		X	
4/16/2021	X	X	
5/7/2021	X	X	
5/21/2021		X	
6/1/2021	X	X	
6/15/2021		X	
7/6/2021	X	X	storm #2
7/20/2021		X	
7/29/2021		X	storm #3
8/5/2021	X	X	
8/26/2021		X	

Table 2. Coordinates of monitoring sites.

Site	Latitude (°N)	Longitude (°W)
Lake	42.96555	85.59541
Tributary	42.96432	85.59110
Outlet	42.96637	85.59719

Results

East Beltline Drainage Tributary

Overall mean annual values of the tributary indicated relatively high dissolved oxygen (DO) concentrations, an alkaline system (i.e., pH > 7), with elevated P, Cl^-, and conductivity (Table 3). These data are generally consistent with an urban stream; the high mean Cl^- and conductivity values are consistent with a stream being impacted by road salt.

Table 3. Tributary mean (±SD) baseflow water quality for n=25 sampling events from August 2020 through August 2021.

Variable	Mean Baseflow (±SD)
Temp (°C)	12.6 (7.3)
DO (mg/L)	11.1 (2.0)
DO (%)	103.3 (9.6)
pH	8.2 (0.2)
SpCond (µS/cm)	1772 (429)
TDS (g/L)	1.17 (0.28)
Turbidity (NTU)	16.3 (44.8)
Cl^- (mg/l)	335 (126)
TP (µg/L)	11 (8)
SRP (µg/L)	29 (16)

Tributary water temperature throughout the monitoring year followed seasonal trends that are typical for this region, with lower temperatures in the winter months and warmer temperatures in summer months (Fig. 2A). Colder water has greater capacity to hold higher DO concentrations compared to warmer water, and we observed that DO in the tributary followed this trend (Fig. 2B). pH was stable throughout the year, and indicated slightly alkaline (basic) conditions (Fig. 2C). Turbidity was highly variable and peaked during the rainy fall and spring seasons (Fig. 2D). TDS and SpCond spiked in February and were highest during the observed rain-on-snow melting event, indicating that runoff entering the tributary was carrying road salts, but interestingly, both these parameters declined after the October storm event, likely due to dilution from non-salt contaminated runoff (Fig. 2E, F).

Tributary Cl^- concentrations were generally highest during winter months, peaking at 954 mg/L during February's snowmelt event, declining in spring and then fluctuating between 200 and 400 mg/L throughout summer and fall (Fig. 3). Cl^- concentrations closely mimicked specific conductivity, indicating that Cl^- was heavily influencing the conductivity values (Figs. 2, 3). TP peaked at 170 µg/L in October and was variable at < 80 µg/L throughout the rest of the monitoring year.

Comparison of storm flow vs. baseflow events revealed that Cl^- is either diluted (Oct 12, July 6) or little impacted (July 29) by storms, and that the concentration of Cl^- in the tributary during baseflow decreases throughout the year following the winter peak (~700 mg/L in February to ~300 mg/L in October), but does not drop below the EPA threshold (Fig. 4). There was a significant Cl^- concentration decline during the October storm (to 7 mg/L) but it rebounded to near pre-storm concentrations within one week (Fig. 4). The Cl^- concentrations during the snowmelt event increased almost two-fold, most likely due to both runoff of recently applied deicing salt and salt that accumulated in melting snow banks. TP concentration almost doubled in response to storm events in October 2020 and early July 2021, although the October stormflow peak was much higher than in July; snowmelt also resulted in a doubling of TP concentration (Fig. 4). SRP concentration also increased after both the October storm and snowmelt, but changed little after the July storms (Fig. 4).

During initial phases of tributary monitoring in late summer and fall 2020, the tributary was additionally measured at an upstream site closer to the East Beltline drainage. Physical and chemical water quality parameters, with the exception of SRP, were generally very similar between the two sites (Table 4). As a result of the lack of obvious differences and in order to respect project resource limitations, the upstream site was discontinued from future sampling for the rest of this initial monitoring year. It is possible that upstream-downstream differences within the tributary could exist during the winter and spring seasons during salt application and snowmelt events.

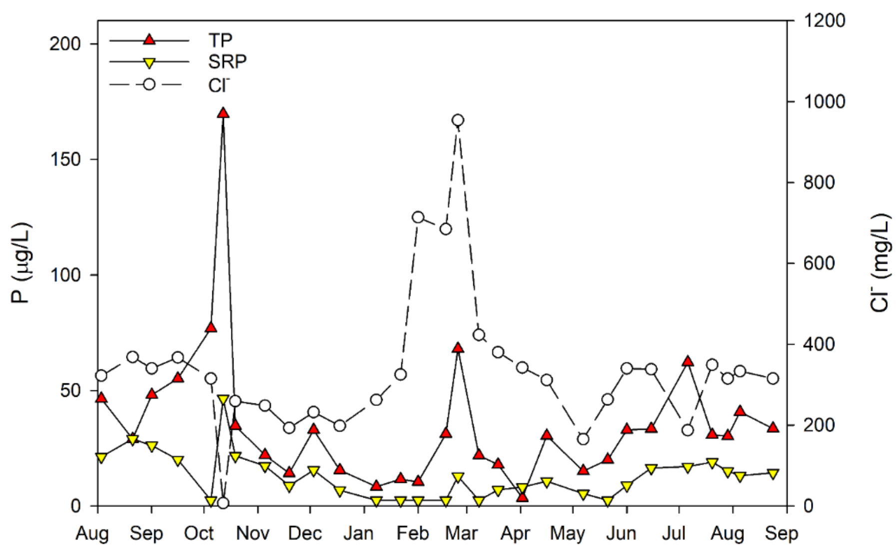

Figure 3. Church Lake tributary TP, SRP, and Cl^- from August 2020 through August 2021. Note that the baseflow, storm flow (10/13/20 and 7/29/21), and snowmelt (2/24/21) sampling events are included in this figure.

Table 4. Tributary mean (±SD) water quality at upstream vs. downstream sites. For both columns, mean values represent n=3 baseflow sampling events from August through September 2020.

	Mean Upstream (±SD)	**Mean Downstream (±SD)**
Temp (°C)	20.0 (1.4)	19.6 (0.5)
DO (mg/L)	9.6 (0.9)	9.2 (1.5)
DO (%)	105.67 (8.34)	100.73 (14.93)
pH	8.01 (0.08)	8.09 (0.15)
SpCond (µS/cm)	1832 (152)	1831 (163)
TDS (g/L)	1.191 (0.099)	1.190 (0.106)
Turbidity (NTU)	13.0 (7.0)	4.3 (0.9)
Cl^- (mg/l)	358 (45)	358 (16)
TP (µg/L)	38 (12)	44 (13)
SRP (µg/L)	15 (1)	25 (5)

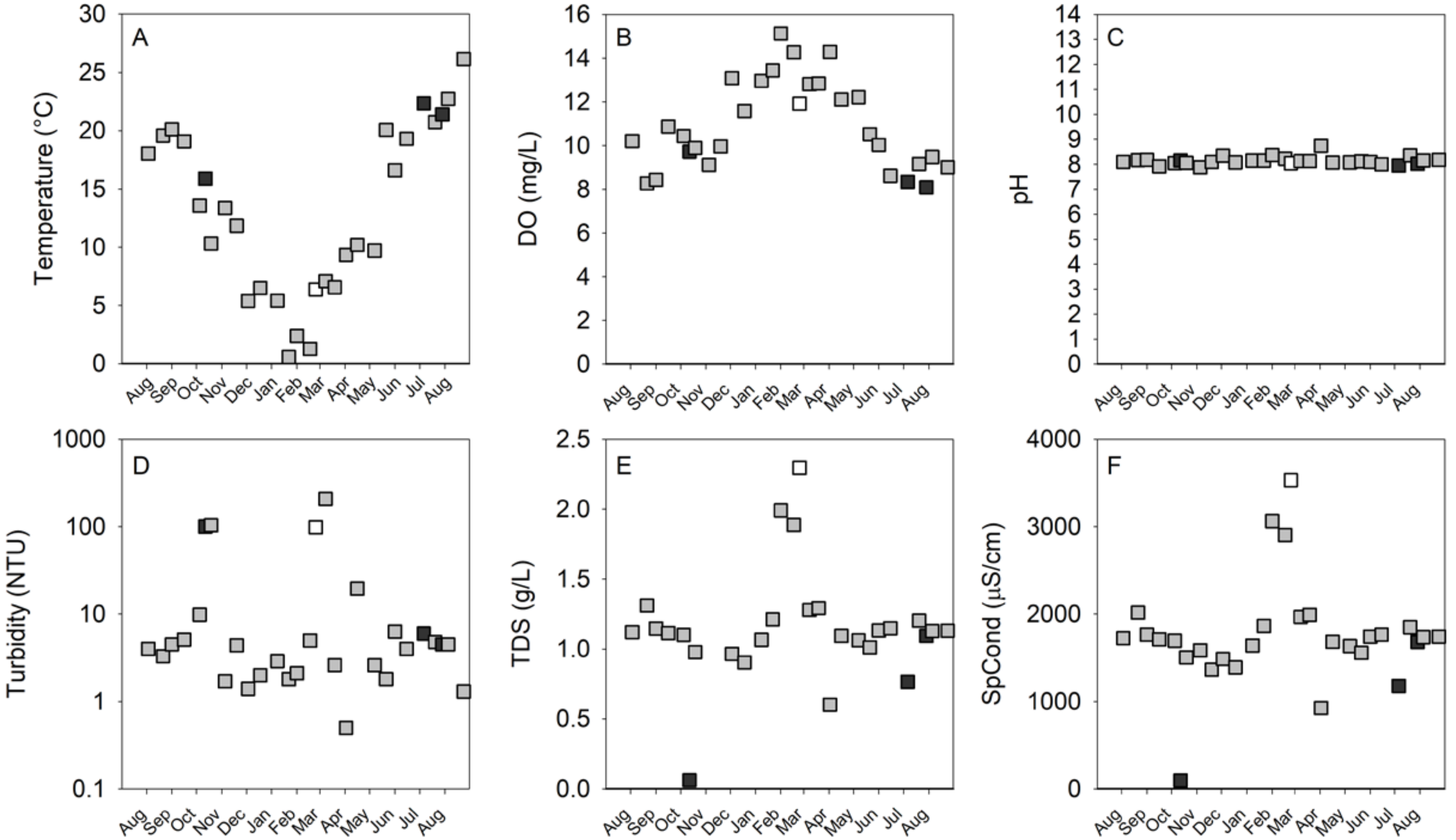

Figure 2. Temperature, dissolved oxygen (DO), pH, turbidity, total dissolved solids (TDS), and specific conductivity (SpCond) of Church Lake's Beltline Avenue drainage tributary at from August 2020 through August 2021. Three storm flow events (10/13/20, 7/6/21, and 7/29/21) are marked with black symbols. The rain on snow melting event (2/24/21) is marked with a white symbol. Note y-axis for turbidity is a log scale.

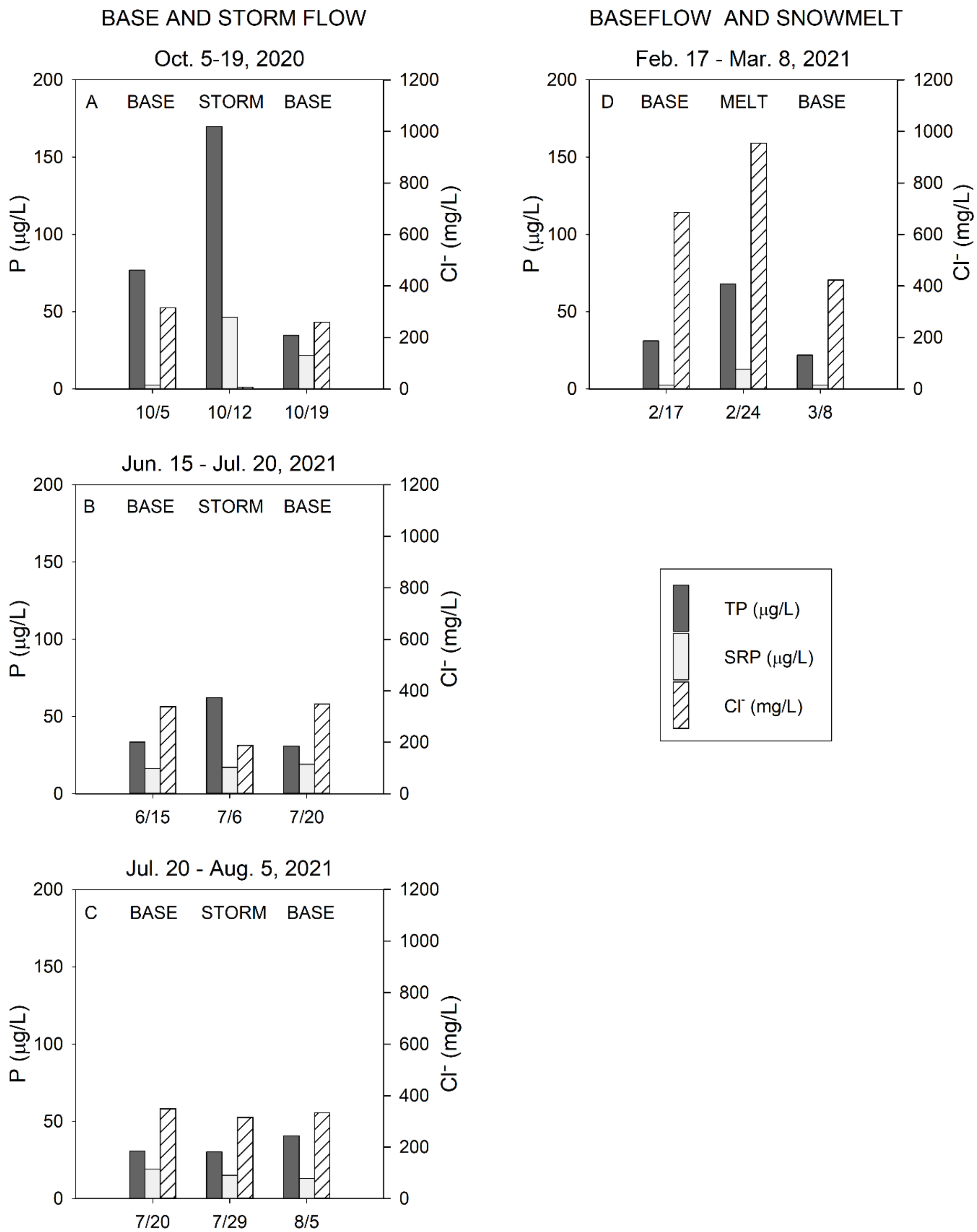
BASE AND STORM FLOW
Oct. 5-19, 2020
A BASE STORM BASE
10/5 10/12 10/19
BASEFLOW AND SNOWMELT
Feb. 17 - Mar. 8, 2021
D BASE MELT BASE
2/17 2/24 3/8
Jun. 15 - Jul. 20, 2021
B BASE STORM BASE
6/15 7/6 7/20
Jul. 20 - Aug. 5, 2021
C BASE STORM BASE
7/20 7/29 8/5
P (µg/L)
Cl- (mg/L)
TP (µg/L)
SRP (µg/L)
Cl- (mg/L)

Figure 4. Enhanced views of Church Lake tributary TP, SRP, and Cl^- during storm and snowmelt events on (A) Oct. 13, 2020; (B) Feb. 24, 2021; (C) July 6, 2021; and (D) July 29, 2021. Baseflow events that were measured before and after each storm or snowmelt event are provided for context.

Church Lake

Physical and chemical measurements from Church Lake's deep hole are presented here, with descending rows corresponding to increasing depth and columns different sampling events over time. Color coding is used to highlight gradients in water quality.

Water temperature showed a fairly distinct gradient in summer months, with warmer temperatures in the top 3 m (≥ 25°C), and colder temperatures below 6 m throughout the year except for the July 2021 sampling event (Table 5). This large storm event (see Fig. 6) may have temporarily pushed surface waters to deeper depths, resulting in short-term increases in temperature. Surface waters were well-oxygenated and ranged between 6 and 13 mg/L in near-surface depths; however, DO values below 12 m were all very low (< 1 mg/L), and indicative of stressful conditions (Table 6). The July 2021 samples with somewhat higher DO concentrations at the 9 and 12m depths may have been partially attributable to storm-induced, short-term mixing, but it also may be due to sampling problems, as the crew did not have the long cable for the YSI sonde that day; instead they used the Van Dorn sampler to collect samples at the bottom and then brought them up to the surface for measurement of parameters, which may have resulted in artificial elevation of DO (and maybe temperature, as well).

Table 5. Church Lake monthly water temperature (°C) results by sampling date and depth. Crossed-out boxes indicate that data were not collected at that depth and date. The water temperature 3-color scale gradient ranges from 0°C as dark blue (water freeze point; = 32°F) to 40°C as dark red (hot; = 104°F), and 20°C as white (room temperature; = 68°F).

Depth (m)	8/3/2020	9/1/2020	10/5/2020	11/5/2020	12/3/2020	2/1/2021	4/16/2021	5/7/2021	6/1/2021	7/6/2021
0	26	25	16	10	4	2	12	14	20	28
3		25	16	9		3	9	13	17	22
6		10	12	9		3	5	5	7	9
9	5	5	5	6	5	4	4	4	5	10
12		5	5	5		5	5	5	5	12
15	5	5	5	5	5	5	5	5	5	12

Table 6. Church Lake monthly dissolved oxygen (mg/L) results by sampling date and depth. Crossed-out boxes indicate that data was not collected at that depth and date. The DO 3-color scale gradient includes 0 mg/L as dark red (anoxic), 2 mg/L as yellow (threshold of low oxygen, or hypoxia), and > 5 mg/L as green (oxic).

Depth (m)	8/3/2020	9/1/2020	10/5/2020	11/5/2020	12/3/2020	2/1/2021	4/16/2021	5/7/2021	6/1/2021	7/6/2021
0	8.6	8.4	8.6	9.4	8.6	12.8	11.6	10.5	9.8	8.7
3		7.9	8.5	8.7		9.4	12.6	10.5	7.7	6.4
6		2.2	0.9	7.9		6.0	2.5	1.9	1.1	4.3
9	1.2	0.8	0.5	1.7	6.1	1.4	0.3	0.3	0.4	2.6
12		0.5	0.3	0.9		0.7	0.4	0.4	0.5	2.4
15	0.5	0.4	0.3	1.5	0.6	0.5	0.7	0.3	0.6	0.8

Church Lake pH was fairly consistent throughout the year with the exception of a slight decline at surface and near-surface depths in the winter; otherwise, pH followed the trend expected in a stratified lake, with surface waters ranging ~7.5-8.5 and bottom waters ranging ~6.5-7.5 (Table 7).

Table 7. Church Lake monthly pH results by sampling date and depth. Crossed-out boxes indicate that data was not collected at that depth and date. The pH 3-color scale gradient includes 6 as yellow (slightly acidic), 7 as light green (neutral), and 8 as dark green (slightly basic).

Depth (m)	8/3/2020	9/1/2020	10/5/2020	11/5/2020	12/3/2020	2/1/2021	4/16/2021	5/7/2021	6/1/2021	7/6/2021
0	8.6	8.4	8.3	7.7	7.6	7.9	8.7	8.6	8.6	8.6
3		8.4	8.3	7.5		7.7	8.7	8.5	8.3	8.0
6		7.8	7.5	7.5		7.5	7.4	7.3	7.4	7.2
9	7.6	7.1	7.1	6.7	7.6	7.2	7.1	7.0	6.9	7.4
12		6.8	6.8	6.5		6.5	6.4	6.4	6.5	6.7
15	6.9	6.7	6.7	6.5	6.4	6.5	6.4	6.5	6.5	7.1

Specific conductance was high throughout Church Lake (Table 8). Values above 600 µS/cm in freshwater systems suggest that they are impaired (Steinman et al. 2011); all our samples in Church Lake exceeded that threshold. In addition, there was a distinct vertical gradient of specific conductivity with bottom waters (~1800 µS/cm) almost twice as high as surface waters (~900 µS/cm). This indicates that dissolved salts and other dissolved ions are sinking to the bottom depths. Although mixing does not appear to occur, the surface conductivity is still higher than expected or desired for most MI inland lakes, and suggests there is a residual salt effect even in the surface waters. This also has implications for lakes downstream of Church (i.e., Middleboro and West Lakes) because the surface connections will allow salt to move out of Church Lake during high flow events, and potentially contaminate those other systems. TDS followed the same trend as conductivity, with surface waters having a normal range for freshwater (< 1 g/L) while bottom waters were more indicative of saline waters (1-3 g/L; Appendix 1).

The typical range of Cl^- concentrations from natural sources in lakes is 0 to 10 mg/L (Hintz and Relyea 2019). It is clear that Church Lake is experiencing uncommonly high Cl^- concentrations at all depths and especially at the lake bottom, with concentrations ranging 114-172 mg/L being regularly found at the surface and exceeding 300 mg/L at bottoms depths (Table 9).

Table 8. Church Lake monthly specific conductance (µS/cm) results by sampling date and depth. Crossed-out boxes indicate that data was not collected at that depth and date. The conductance color scale is an even gradient between the smallest (green) and largest (yellow) values.

Depth (m)	8/3/2020	9/1/2020	10/5/2020	11/5/2020	12/3/2020	2/1/2021	4/16/2021	5/7/2021	6/1/2021	7/6/2021
0	817	839	847	863	810	913	883	895	899	838
3		838	846	864		918	897	894	901	871
6		955	956	864		938	931	933	927	927
9	1108	1343	1405	1349	890	1117	1182	1210	1224	999
12		1760	1768	1746		1764	1742	1742	1733	1626
15	1775	1784	1798	1791	1764	1813	1761	1755	1746	1725

Table 9. Church Lake monthly Cl^- (mg/L) results by sampling date and depth. The Cl^- color scale refers to values below (white) and above (red) the US EPA's chronic freshwater aquatic life water quality criterion of 230 mg/L.

Depth (m)	8/3/2020	9/1/2020	10/5/2020	11/5/2020	12/3/2020	2/1/2021	4/16/2021	5/7/2021	6/1/2021	7/6/2021
0	142	154	158	132	155	172	114	167	267	155
3	141	157	171	162	166	123	164	169	175	160
6	157	166	167	163	169	175	168	154	178	172
9	211	206	194	204	167	203	187	169	195	185
12	279	280	281	256	256	199	249	263	277	307
15	279	323	249	291	277	246	313	284	310	324

The TP concentrations in the Church Lake surface waters were generally acceptable in all months except winter, being less than the commonly accepted threshold for impairment of 25 µg/L (Table 10). It is possible that phosphorus accumulates in winter because the colder temperatures reduce biological activity. However, TP concentrations in the bottom depths at 9, 12, and 15 m were 2-3 orders of magnitude (100 - 1000×) greater than those at the surface, with an alarmingly high maximum TP concentration of 6,222 µg/L in July 2021 (Table 10, Fig. 3).

Because SRP concentrations reflect the amount of *bioavailable* phosphorus in the water column, their concentrations can be deceiving. Unlike TP, low amounts of SRP do not necessarily indicate good water quality; a low level of SRP can arise because this bioavailable form of P has been taken up by the algae, and all the phosphorus is now stored in the algal cells (and now reflected in TP) instead of in the water column. Hence, the below detection levels of SRP (< 3 µg/L) in the top 6 m of Church Lake (Table 11) are most likely due to algal uptake. At greater depths, where there is insufficient light penetration to allow algae to photosynthesize and grow, the SRP concentrations once again increase to very high levels, and account for 80 to 90% of the TP on most sampling dates (Table 11).

Table 10. Church Lake monthly TP (µg/L) results by sampling date and depth. The TP color scale references Carlson's (1996) relationships between phosphorus concentrations and lake trophic class, such that concentrations ranging 0-12 µg/L are oligotrophic (green), 12-24 are mesotrophic (green-yellow), 24-96 are eutrophic (orange-red), and >96 are hypereutrophic (red-black).

Depth (m)	8/3/2020	9/1/2020	10/5/2020	11/5/2020	12/3/2020	2/1/2021	4/16/2021	5/7/2021	6/1/2021	7/6/2021
0	14	12	16	20	66	77	18	9	22	23
3	19	12	16	16	67	62	36	13	25	26
6	28	23	27	4	70	70	40	36	33	61
9	488	523	290	501	271	266	87	103	122	59
12	3694	3179	3277	3255	4293	1221	2259	2847	3132	4351
15	5003	4436	5051	4829	4698	2935	4711	4316	4322	6222

Table 11. Church Lake monthly SRP (µg/L) results by sampling date and depth. Note that trophic classes have not been established for SRP, so this SRP color scale simply represents the lowest (white), middle (red shades) and highest (black) observed values.

Depth (m)	8/3/2020	9/1/2020	10/5/2020	11/5/2020	12/3/2020	2/1/2021	4/16/2021	5/7/2021	6/1/2021	7/6/2021
0	5	5	5	5	28	26	5	5	5	5
3	5	5	5	5	28	53	5	5	5	5
6	5	5	5	5	28	53	5	5	13	5
9	355	466	205	468	121	234	50	33	60	27
12	3254	2753	2910	2805	3620	1114	2112	2607	3023	3373
15	4435	3819	4529	3845	4210	2595	1497	3910	4055	4581

We summarize the Church Lake Cl^-, TP, and SRP data through time and water depth in Fig. 5. Chloride concentrations increase with depth; concentrations are relatively low in the top panels at 0 to 6 m but almost double in the bottom panels at 12 and 15 m. With respect to season, Cl^- is very stable over time at each depth except the surface, where a substantial spike can be observed in June 2021 (Fig. 5). This reflects the greater sensitivity of the surface layer to salt runoff; its occurrence in June may seem surprising, but after big rain events like those in June 2021 (Fig. 6), the Cl^- stored in soils or on roadways can run off and elevate salt concentrations in shallow groundwater, tributaries, and lakes in the short-term (Burgis et al. 2020). Preliminary results from laboratory experiments we are conducting with the Church Lake tributary soils indicate similar results with Cl^- release from the soil after simulated rain events (J. Molloseau, unpublished data).

Both TP and SRP also increased with depth in Church Lake but unlike Cl^-, the increases were much more dramatic – from ~20 to ~5,000 µg/L (Fig. 5). The TP concentrations were relatively stable throughout the year at each depth, even as they increased in amount. This contrasts with SRP, which showed seasonal fluctuations at the shallower depths, likely related to algal growth. However, below 9 m, when light limited algal growth, SRP concentrations stabilized throughout the year (Fig. 5).

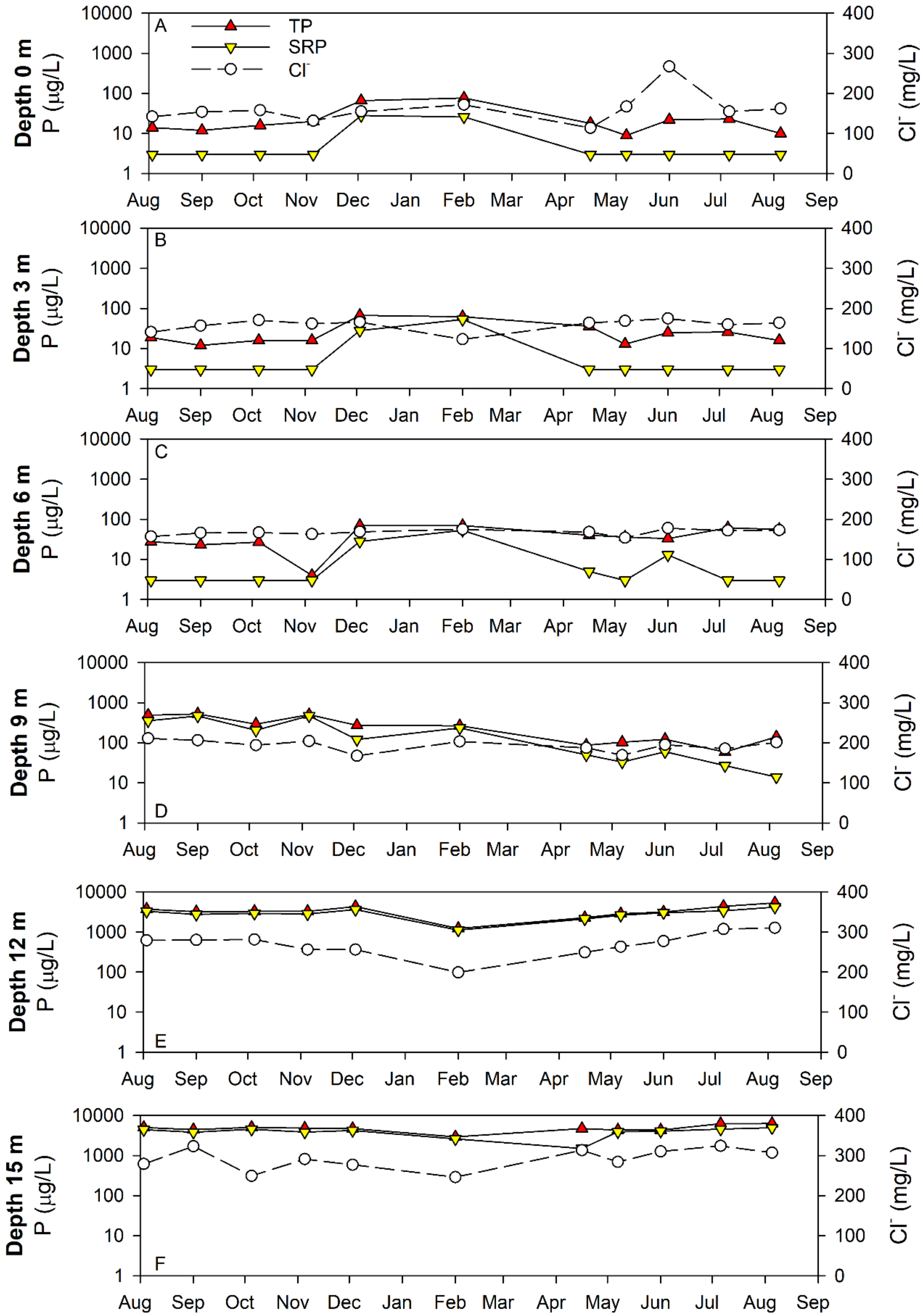

Figure 5. Church Lake water chemistry (TP, SRP, Cl^-) by depth and date from August 2020 – August 2021. Note that TP and SRP share a logarithmic y-axis scale while Cl^- has a separate normal scale. Legend in panel A applies to all panels.

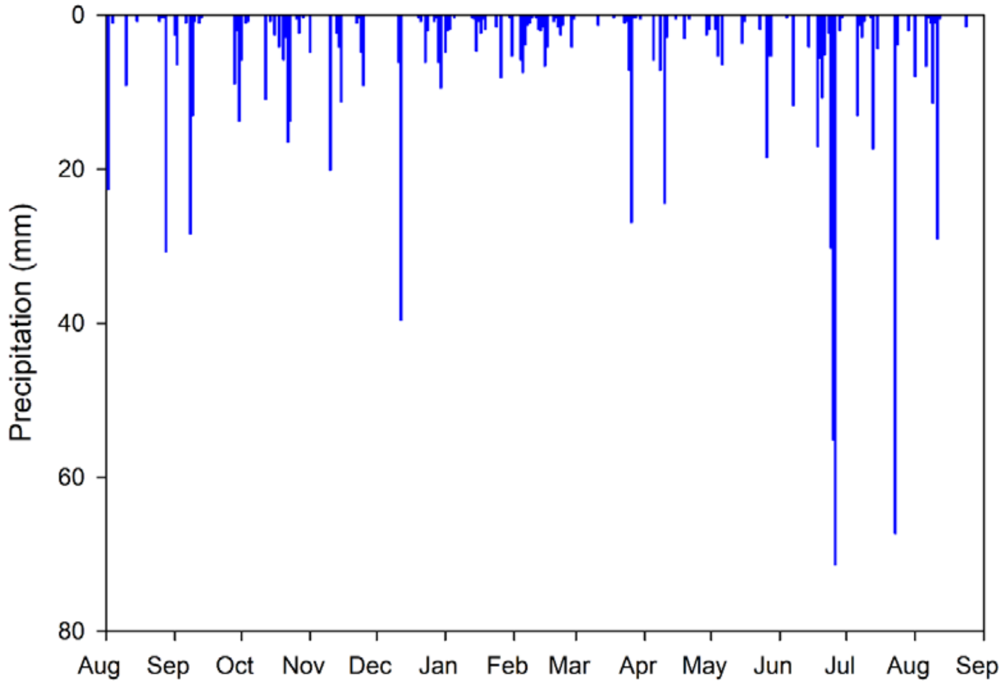

Figure 6. NCEI daily precipitation totals at GRR from August 2020 - August 2021

Discussion

The salinization of freshwater ecosystems is a growing concern throughout the world. Although there are multiple sources of salt, road deicing salts have attracted growing attention from applicators, environmentalists, regulators, and scientists.

The application of road deicing salts provides a societal benefit by improving road safety during dangerous winter conditions. Studies have shown that accident rates decline by over 75% after salt application (Usman et al. 2010). However, there is an environmental cost associated with this application. Road salts will dissolve and enter freshwater ecosystems through overland runoff into storm drains, tributaries, and shallow groundwater. Chloride is a conservative ion, and as such is not readily broken down or utilized; its persistence in the environment can present concerns for long periods of time. In addition, road salt contamination is not just a winter problem; chloride can be detained in shallow groundwater or in soils flooded during spring runoff, resulting in slow release throughout the year after rain events (Kelly et al. 2008; Burgis et al. 2020).

Unimpacted freshwater systems usually have chloride concentrations that are less than 20 mg/L but concentrations can be significantly elevated after exposure to road salts. Groundwater directly under stormwater management ponds that detain road salt runoff contained a mean chloride concentration as high as 3,828 mg/L and a maximum concentration of 18,540 mg/L (Snodgrass et al. 2017), which is about ¼ the concentration of seawater. Excess chloride has both biological and geochemical implications. Biologically, Cl^- concentrations even below the US EPA chronic water quality criterion of 230 mg/L can change the community composition of algae and aquatic plants, reduce sensitive macroinvertebrates, and eliminate sensitive fish species. At higher concentrations, not only will there be greater disruption to system biology, but lake turnover will be affected due to the establishment of a salt gradient, which in turn can lead to depletion of dissolved oxygen and accumulation of nutrients and various metals in bottom waters (Hintz and Relyea 2018).

Our study did not address the effect of salt on the biology of Church Lake, but this is an issue that homeowners may want to consider in the future. Rather, we focused on characterizing the effect of salt on the lake's chemical and physical status. Our results clearly show that Church Lake is suffering from both excess Cl^- and phosphorus. The high Cl^- concentrations have created a salt gradient in the lake, such that the deeper parts of the lake no longer fully mix; this lack of seasonal turnover, which has been observed in other Michigan lakes (Bridgeman et al. 2000; Sibert et al. 2015), allows nutrients and metals to accumulate in the bottom waters. Phosphorus concentrations are extremely high at the deepest depths, at times being ~20 to 200× greater than desirable, and if the lake were to turn over, very likely would result in a major algal bloom. Hence, the current lake system is something of a ticking time bomb, but still with a modestly long fuse.

Given these conditions, it is essential that any restoration plan deal first with the phosphorus. Our concern is that if the salt concentrations were to be reduced as a first step, the loss of the salt gradient would allow the lake to turn over, and the excess P in the bottom waters would reach the lake surface. When combined with sunlight (which is unavailable at the bottom depths), the P would very likely stimulate substantial, and possibly toxic, algal blooms.

Instead, we recommend a first step of chemical inactivation of phosphorus, likely in the form of either Phoslock or alum, to bind the phosphorus in place and reduce the concentration in the water column (Lürling et al. 2020) to 25 µg/L or less throughout the lake. While blooms may still form at that concentration, they are more easily contained with algaecide applications. Chemical inactivation of phosphorus is a proven technology, and has been used in other west Michigan lakes with varying results. The inactivant can strip phosphorus out of the water column as it settles down to the lake bottom, and then help prevent additional phosphorus from diffusing out of the sediment and into the water by binding it as a solid. Current work suggests that this type of internal phosphorus loading is in fact occurring in Church Lake at modest rates, and is exacerbated by the presence of chloride (E. Foley, unpublished data). Depending on how much control is applied to new P entering Church Lake from external sources, a chemical inactivant treatment could last anywhere from 1 to 20 years.

Once the P concentrations have been reduced (and this may take several applications of a chemical inactivant given the very high P concentrations), then the salt issue can be addressed. Desalination is a very expensive process using standard technologies (e.g., reverse osmosis) being employed at large scales for municipal drinking water supply. This is clearly inappropriate for a small lake like Church. We recommend exploring the feasibility of two approaches, which are not mutually exclusive:

- Redesign the runoff from East Beltline so instead of it entering directly into the tributary, it enters a retention/detention basin, where the salt has a better chance to be retained or redirected to a sanitary sewer system, assuming that Grand Rapid's wastewater treatment facility can handle high salt concentrations. Depending on the geophysical characteristics of the retention basin, the salt ions may end up entering the groundwater and eventually reaching

Church Lake, so it is critical that any design take this possibility into consideration. A series of shallow and deep wells can be installed and monitored for chloride concentrations to determine the sources of contamination, which is critical for effective control and management of the salt problem.

- Address the in-lake salt and phosphorus issues. We suggest two possible options, both of which would need preliminary testing to assess their feasibility and efficacy.
    - Hypolimnetic withdrawal (pumping salt-rich from the bottom of Church Lake): in this approach, a portion of undeveloped land abutting the lake would be dedicated for clearing the land of vegetation, and then placing an impermeable liner on the ground to create an artificial, shallow basin. Bottom water would be pumped on top of the liner and allowed to evaporate—the evaporation could be enhanced by placing heating elements underneath the liner, perhaps powered by photovoltaic panels. Once evaporation is complete, the residual salt would be scraped off the liner, and a new volume of water would be pumped onto the liner surface. The time to desalinate the lake would depend on multiple factors, including the volume of water the liner could handle, the rate of evaporation, and the degree to which new salt is prevented from entering Church Lake. To our knowledge, this approach has not been tested elsewhere.
    - Sediment oxidation: This can be done with either chemical additions (e.g., calcium nitrate, iron chloride (probably not a good choice for Church Lake), and lime) to serve as electron acceptors in place of depleted oxygen or with hypolimnetic aerators to inject oxygen to the bottom water layers. This is very different than aerators installed at the surface of lakes are designed to break down lake stratification to prevent algal bloom formation. In contrast, hypolimnetic aerators would be designed to make sure the lake stratification does not break down (so the phosphorus does not reach the surface of Church Lake), but provides oxygen at the bottom to bind the phosphorus to iron and other elements, and minimize the formation of potentially toxic levels of hydrogen sulfide. The most common type of hypolimnetic aerators are airlift aerators, Speece cones, and deep oxygen injection systems. More details are available in Singleton and Little (2006) and Cooke et al. (2016). As with hypolimnetic withdrawal, it would be necessary to conduct tests to determine the appropriate amount of aeration to avoid de-stratification and have a demonstrable benefit to lake chemistry.

Recommendations/Next Steps

1. Work with MDOT and the Kent County Drain Commissioner's Office to stop or reduce salt deicer runoff from entering Church Lake. This should be done as soon as possible, and hopefully before this upcoming winter. In addition, discussion of a retention/detention basin should be broached.

2. Work with chemical applicators (e.g., PLM: https://www.plmcorp.net/) to discuss the feasibility and cost of a chemical application in Church Lake to control phosphorus.

3. Meet with engineering firms to discuss feasibility and cost of a salt removal process, a detention/retention basin, and hypolimnetic aeration systems. Local companies to consider include Prein & Newhof (https://www.preinnewhof.com/contact/) and Fishbeck (https://fishbeck.com/).

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Appendix 1. Total Dissolved Solids.

Church Lake monthly total dissolved solids (g/L) results by sampling date and depth. Crossed-out boxes indicate that data was not collected at that depth and date. The TDS color scale is based on the USGS threshold of freshwater having < 1 g/L (green) and slightly saline water having 1-3 g/L (yellow).

Depth (m)	8/3/2020	9/1/2020	10/5/2020	11/5/2020	12/3/2020	2/1/2021	4/16/2021	5/7/2021	6/1/2021	7/6/2021
0	0.531	0.545	0.551		0.527	0.593	0.574	0.582	0.585	0.545
3		0.545	0.550			0.596	0.583	0.581	0.586	0.566
6		0.621	0.621			0.610	0.605	0.607	0.602	0.603
9	0.720	0.873	0.913		0.578	0.726	0.769	0.786	0.796	0.649
12		1.144	1.149			1.146	1.132	1.132	1.126	1.057
15	1.154	1.16	1.169		1.147	1.179	1.145	1.141	1.135	1.121