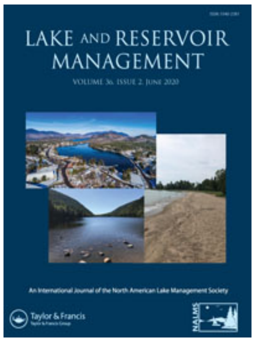

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A reduction in spring mixing due to road salt runoff entering Mirror Lake (Lake Placid, NY)

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ABSTRACT
Wiltse B, Yerger EC, Laxson CL. 2019. A reduction in spring mixing due to road salt runoff entering Mirror Lake (Lake Placid, NY). Lake Reserv Manage. 36:109–121.

Road salt has resulted in the salinization of surface waters across temperate North America. Increasingly, road salt is recognized as a significant regional pollutant in the Adirondack Park. Here we analyze biweekly limnological data from Mirror Lake (Lake Placid, NY) to understand the role of road salt runoff in an apparent lack of spring mixing in 2017. Water column profile data show notable spatial and temporal variability in chloride concentrations within the lake. Concentrations are highest at the lake bottom during the winter, with increases associated with the onset of road salt application to the watershed. High chloride concentrations in the hypolimnion persisted through the summer of 2017 due to a lack of complete spring mixing as the result of road salt induced density differences within the water column. Water density calculations and Schmidt stability point to an increase in water column stability due to the accumulation of salt at the lake bottom. The incomplete spring mixing resulted in greater spatial and temporal extent of anoxic conditions in the hypolimnion, reducing habitat availability for lake trout. Restoration of lake mixing would occur rapidly upon significant reduction of road salt application to the watershed and improvements in stormwater management.

KEY WORDS
Adirondack Park; Lake Placid; lake trout; Mirror Lake; monomixis; road salt; stratification

Road salt commonly is used across temperate North America to maintain roads free of snow and ice in the winter because of its comparatively low cost and availability (TRB 1991). Most of these are chloride-based salts, primarily sodium chloride, although mixtures of calcium chloride and magnesium chloride also are used commonly (TRB 1991). The use of road salt has been increasing steadily over the past 60 yr. In 2014, 24.2 million metric tons of sodium chloride was applied to roads in the United States (Lilek 2017).

Sodium chloride increasingly is recognized as a significant pollutant in the northern hemisphere. Road runoff has infiltrated both surface water and groundwater, resulting in elevated salinity (Kelting et al. 2012, Dugan et al. 2017, Schuler et al. 2017, Hintz and Relyea 2017a, Kelly et al. 2018, Pieper et al. 2018). Sodium and chloride concentrations in impacted waters have been linked to road density, impervious surface density, and road salt application rates (Kaushal et al. 2005, Kelting et al. 2012). Groundwater with concentrations exceeding US Environmental Protection Agency (EPA) drinking-water guidance values for sodium has been documented in areas receiving runoff from general road application, as well as runoff from salt storage facilities (Kelly et al. 2018, Pieper et al. 2018).

Road salt has the potential to upset ecosystem structure, resulting in undesirable shifts in ecological communities (Hintz et al. 2017). The impact of road salt on aquatic life varies by species, ecosystem, and the type of salt applied (Jones et al. 2015, Hintz and Relyea 2017b). In urban areas, surface waters may exceed the EPA chloride thresholds for chronic and/or acute chloride toxicity to aquatic life (Corsi et al. 2015). However, the EPA

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thresholds for acute and chronic toxicity from chloride may not be directly relevant to a particular lake or stream ecosystem. Specifically, taxa in oligotrophic soft-water lakes may be more sensitive to chloride pollution (Elphick et al. 2011, Brown and Yan 2015). The addition of multiple stressors, such as climate change, acid deposition recovery, and eutrophication, further complicates our understanding of how aquatic ecosystems will respond to elevated salinity (Palmer and Yan 2013).

The impact of road salt runoff on the physical limnology of North American lakes is less well known. A few studies have documented meromixis in lakes in urban environments, as a result of salt-induced density gradients (Judd 1970, Novotny et al. 2008, Novotny and Stefan 2012, Sibert et al. 2015, Wyman and Koretsky 2018, Dupuis et al. 2019). The disruption of a physical processes such as lake mixing has indirect effects on both the chemistry and biology of the lake (Judd et al. 2005). Incomplete mixing increases the likelihood of anoxia in the hypolimnion, resulting in the release of phosphorus from sediments, as well as the accumulation of manganese, ferrous iron, sulfide, and methane in the hypolimnion (Wetzel 2001). Prolonged periods of anoxia also can reduce habitat availability for cold stenotherms, such as lake trout (*Salvelinus namaycush*). Lake trout have been declining across their native range in New York State and the state has classified them as a "Species of Greatest Conservation Need" (Carlson et al. 2016). Invasive sea lamprey and climate change are the two major factors affecting lake trout populations in New York State (De Stasio et al. 1996, Schneider et al. 1996). Reductions in habitat availability due to an interruption of lake mixing has the potential to further challenge this species.

Small urban lakes receiving direct stormwater runoff are typically most susceptible to the deleterious effects of road salt pollution (Dupuis et al. 2019, Scott et al. 2019). Mirror Lake in the Village of Lake Placid is the most developed lake in the 6 million acre Adirondack Park. The village is surrounded by New York State Wilderness, resulting in concentrated urban development around Mirror Lake. The goal of this study was to assess the extent to which road salt is responsible for an apparent incomplete spring mixing in Mirror Lake.

Study site

Mirror Lake (44.290°N, 73.982°W) is a small lake in the eastern portion of Essex County in the Adirondack Park of upstate New York. The lake has a surface area of 50 ha, a maximum depth of 18 m, and a volume of 3.42×10^6 m^3. The watershed is 301 ha and is composed of 51% forest, 27% developed, 20% surface water, and 2% wetland. The development is concentrated directly around the lake, with the headwaters of the watershed forested. The lake has one major natural inlet at the north end, but also receives runoff from 22 stormwater outfalls that discharge runoff directly to the lake. The lake outlets at the south end through a culvert that eventually enters the Chubb River. There are 1.1 km of state road and 7.6 km of local road within the watershed. The lake shore is entirely encompassed by road, a combination of both state and local. State roads in the Adirondack Park receive 3 times higher salt loads than local roads (Kelting et al. 2012). Within the watershed there are 28.0 ha of impervious surfaces (9% of watershed area) that may be treated with road salt, with the largest being parking lots (8.3 ha), followed by village roads (5.9 ha), private roads (3.7 ha), driveways (3.5 ha), town roads (2.5 ha), village sidewalks (2.0 ha), state roads (1.2 ha), and private sidewalks (0.9 ha) (Wiltse et al. 2018).

The watershed bedrock material is made up of granite gneiss, migmatite, and olivine metagabbro (Caldwell and Pair 1991). These are common parent materials in the Adirondack uplands and contain very little chloride; as a result, natural chloride concentrations in least impacted Adirondack lakes seldom exceed 1 mg/L (median = 0.24 mg/L; Kelting et al. 2012). The bedrock is overlaid by till and till moraine in much of the watershed, with exposed bedrock in the upper portions of the watershed. Soils consist of the Hermon series directly around the lake and Becket series in the rest of the watershed. These soils are well drained or somewhat excessively drained and commonly occur on glacial till.

The fish community consists of rainbow trout (*Oncorhynchus mykiss*), lake trout (*Salvelinus namaycush*), white sucker (*Catostomus commersoni*), smallmouth bass (*Micropterus dolomieu*),

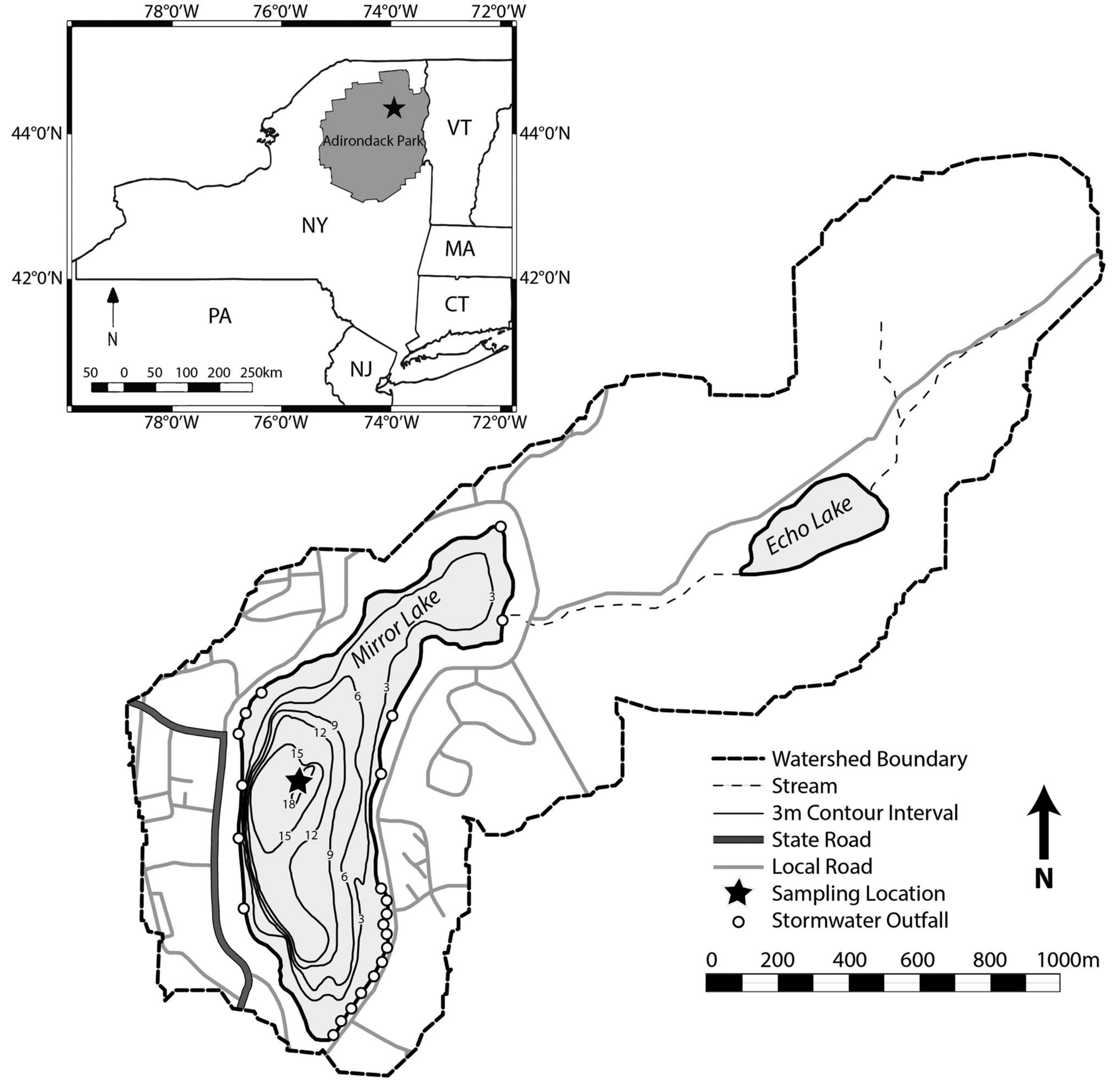

Figure 1. Watershed map of Mirror Lake, including lake bathymetry.

rock bass (*Ambloplites rupestris*), pumpkin seed (*Lepomis gibbosus*), yellow perch (*Perca flavescens*), and brown bullhead (*Ameiurus nebulosus*) (NYSDEC unpublished data). The New York State Department of Environmental Conservation regularly stocks the lake with rainbow trout and lake trout (NYSDEC 2018).

Methods

Mirror Lake was sampled biweekly from 5 December 2015 to 4 January 2018, at the point of maximum depth (18 m, Figure 1). During the period of ice cover, water sampling was conducted monthly by auguring a hole through the ice. Sampling was resumed as soon as possible after ice-out to adequately capture spring mixing. In 2016, sampling resumed 7 d after ice-off, and in 2017 sampling resumed the day of ice-off. Likewise, sampling continued until the formation of ice, to capture the full extent of fall mixing. A YSI Professional Plus multiparameter sonde was used to collected in situ dissolved oxygen, specific conductance, temperature, and pH measurements at 1 m intervals. Water samples were collected at the surface using a 2 m integrated tube sampler and 1.5 m off the bottom (16 m depth) using a 1.2 L stainless steel Kemmerer sampler. Water samples were transferred immediately to acid-washed and field-rinsed sample bottles and transported on ice to the Paul Smith's College Adirondack Watershed Institute for analysis. In the laboratory, samples were passed through a 0.45 µm nylon filter to remove suspended material and were frozen at −30 C until analysis (no more than 28 d). Chloride concentration was determined with chemically suppressed ion chromatography (Lachat Instruments, QC8500, Loveland, CO) following EPA Method 300.1. Quality control measures such as blanks, duplicate samples, and laboratory control samples were analyzed at a frequency of one per batch of 20 or fewer samples and assessed on an ongoing basis. The practical quantitation level of chloride during this study was 0.2 mg/L, and the percent recovery on laboratory control samples (10 mg/L) was 99.8%.

Linear regression was used to develop a lake-specific relationship between specific conductance and chloride. Linear model assumptions were quantitatively assessed using the Global Validation of Linear Models Assumptions (GVLMA) package in R (Pena and Slate 2014, R Core Team 2018). This relationship was used to estimate the concentration of chloride at 1 m intervals through the water column.

Schmidt stability was used to assess changes in the resistance to mixing over the period of the study. Schmidt stability is a measure of the amount of energy required, per unit surface area, to mix the lake to uniform density (Wetzel 2001). Schmidt stability was calculated using a modified version of the rLakeAnalyzer package in R (Winslow et al. 2017). The schmidt.stability() function was modified to use water density equations developed by Chen and Millero (1986). Temperature and practical salinity units (PSU) are used to calculate density. The resulting precision is better than 2×10^{-6} g/cm^3, an improvement over the density calculations used by default in the rLakeAnalyzer package (Millero and Poisson 1981, Martin and McCutcheon 1998). PSU is derived from conductance and temperature measured by the YSI Professional Plus hand-held sonde used to collect water-column profiles (UNESCO 1981). Bathymetric cross-sectional areas were calculated using data provided by the New York State Department of Environmental Conservation (NYSDEC).

Lake trout preferred habitat was estimated using an upper temperature limit of 15 C and lower dissolved oxygen limit of 6 mg/L (Plumb and Blanchfield 2009). The upper and lower limits within the water column were plotted for a visual assessment of shifts in available habitat, and total habitat volume was calculated using bathymetric data.

Results

A linear regression run on all of the paired conductivity–chloride measurements failed to meet the assumptions of a linear regression due to the binomial nature of the data, violating the assumption of a continuous dependent variable. Surface samples had a mean chloride concentration of 44 mg/L, while bottom water samples had a mean of 65 mg/L. To meet the assumptions of a linear regression the 118-sample data set was down sampled to 47 samples to provide a continuous gradient of the dependent variable (chloride). Down sampling was conducted by binning the specific conductance data from 150 to 450 μS/cm in 50 μS/cm increments and then randomly resampling the original data set to obtain a reduced data set with nearly equal frequency across all bins. The data set was reduced sequentially until the resulting regression met the assumption of a continuous dependent variable as evaluated using the GVLMA package in R. The regression results were similar before and after the down sampling ($y = 0.23x - 4.83$, $R^2 = 0.91$, $P < 0.001$; $y = 0.23x - 2.72$, $R^2 = 0.93$, $P < 0.001$, respectively), an indication of the robustness of the relationship and lack of sensitivity to the down sampling (Figure 2). The final regression equation is slightly more conservative in its estimate of chloride.

Temperature at the lake surface ranged from 0.4 C to 24 C, and the lake bottom ranged from 3.1 C to 6.6 C. The lake exhibited a clear pattern of thermal stratification during the summer of

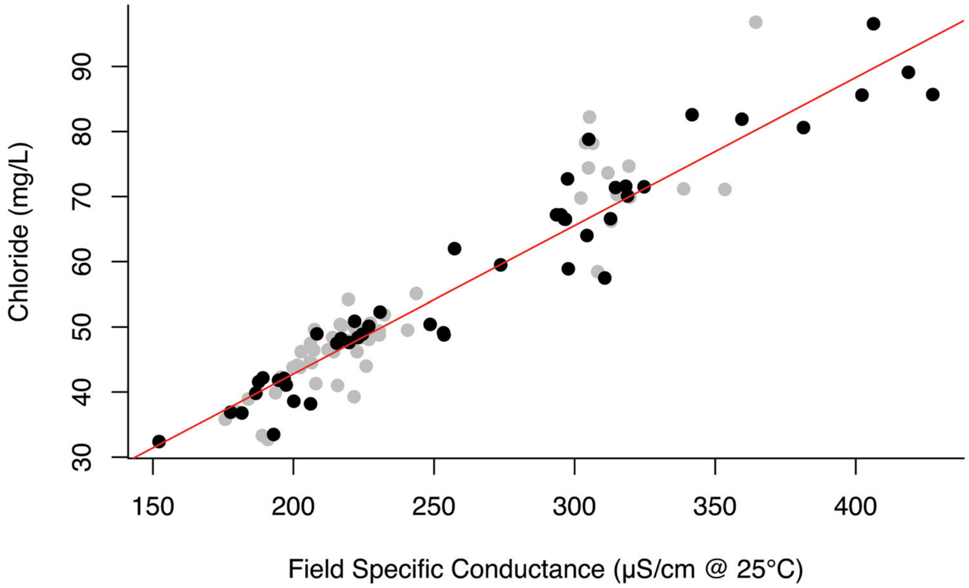

Figure 2. Relationship between conductivity and chloride in Mirror Lake (Lake Placid, NY). $y = 0.23x - 2.72$, $R^2 = 0.93$, $P < 0.001$. Black points are down sampled data; gray points represent data removed through the down sampling process.

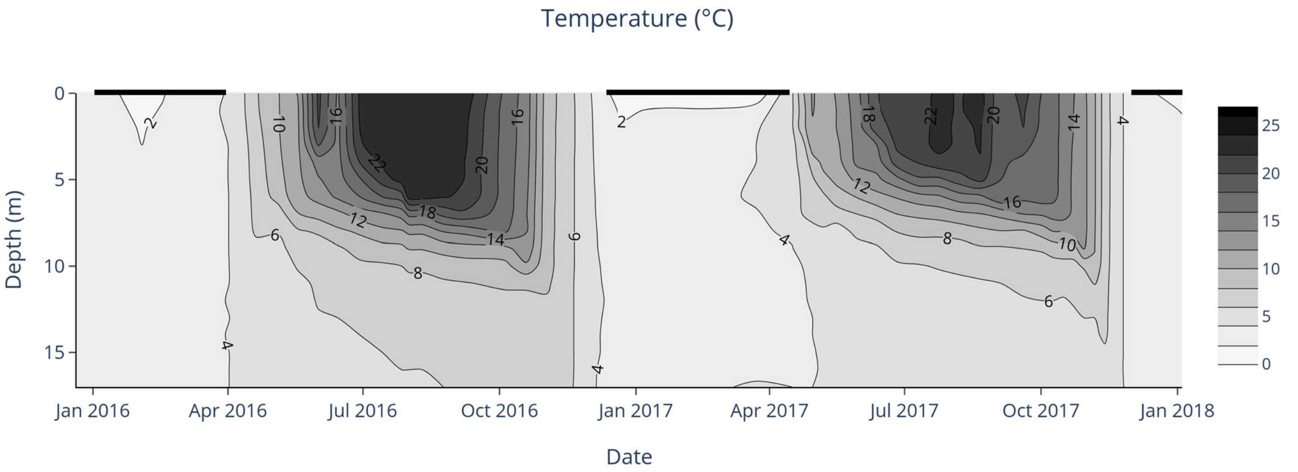

Figure 3. Temperature measured in the Mirror Lake water column. Black bars at the top of the figure indicate periods of ice cover.

both 2016 and 2017, and the lake became isothermal during the spring and fall of each year. The onset of thermal stratification occurred at least 12 d earlier in 2017 than in 2016 (Figure 3).

The spatial and temporal distribution of chloride in the Mirror Lake varied considerably between 2016 and 2017, with concentrations ranging from 19 to 123 mg/L (Figure 4). In both years, concentrations near the lake bottom increased during the winter while salt was being applied to the watershed. In the spring of 2016, concentrations became uniform during spring mixing and remained relatively uniform throughout summer stratification. In the spring of 2017, high concentrations of chloride persisted near the bottom through spring mixing and remained high through summer stratification. Chloride concentrations were uniform during fall mixing in both years. Concentrations at the surface remained fairly constant through 2016 but declined during summer stratification in 2017.

During the winter months, the water column density gradient was driven by elevated salinity near the lake bottom (Figures 4 and 5). The timing and increase in density corresponded with the timing and increase in chloride (Figures 4 and 5). During the summer, the water column density gradient was dominated by temperature. In 2017, when chloride remained high in the

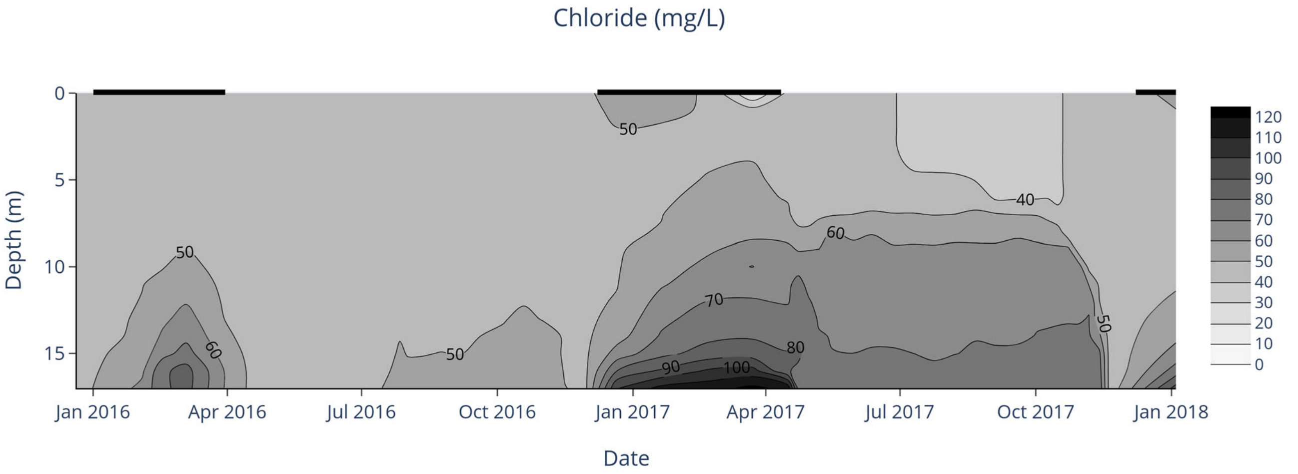

Figure 4. Distribution of chloride in Mirror Lake, modeled from conductivity. Black bars at the top of the figure indicate periods of ice cover.

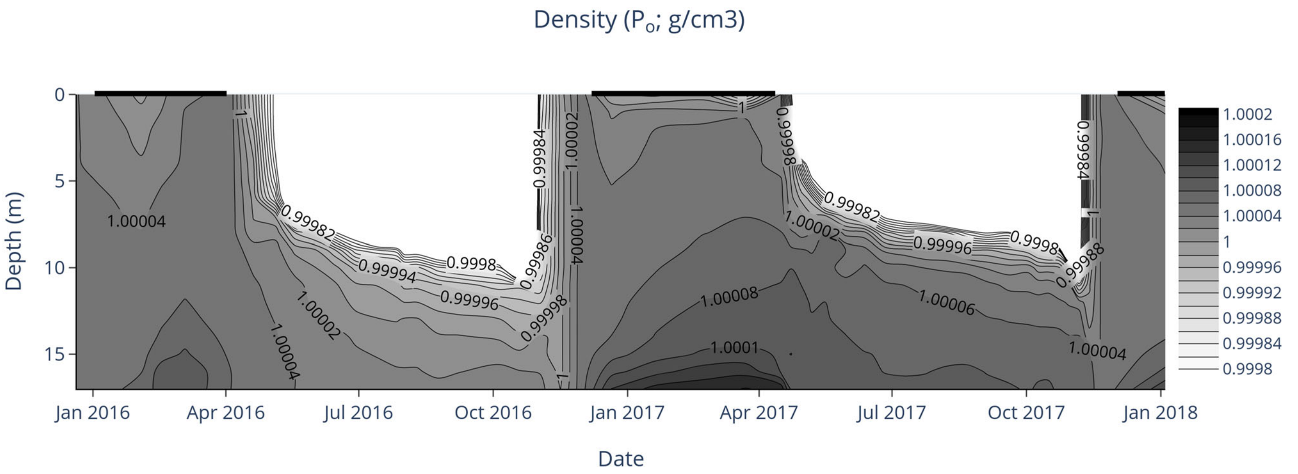

Figure 5. Water density calculated based on temperature and practical salinity units (Chen and Millero 1986). Densities below 0.99980 g/cm^3 are not plotted, for ease of plot interpretation. Black bars at the top of the figure indicate periods of ice cover.

hypolimnion, water density was higher than during the same period in 2016. This is explained partially by a 1 C difference in hypolimnion temperature as well, with hypolimnion temperatures being cooler in 2017.

The hypolimnion was anoxic during summer stratification in both years (Figure 6). The duration and spatial extent of the anoxic conditions were greater in 2017. Anoxic conditions were present at the lake bottom during the winter in 2017, but not in 2016. In both years, a positive heterograde oxygen curve was persistent throughout summer stratification, with the peak dissolved oxygen concentrations occurring at or near the thermocline (Figure 6 and Table 1). Hypolimnetic dissolved oxygen concentrations increased during the spring and fall mixing in 2016 and the fall mixing in 2017. Concentrations increased during spring mixing in 2017, but remained below 6 mg/L (Figure 6).

Temperature was the predominant driver in changes in lake stability (Figure 7). Lake stability dropped by one or more orders of magnitude during the periods of mixing, except during the spring of 2017. Stability during the winter of 2017 was higher than for 2016 because of the salinity-induced water density gradient (Figures 5 and 7). The additional stability in the spring of 2017 because a buildup of salt at the lake bottom increased the stability of the lake to the equivalent of a 3 C increase in surface water temperature.

Lake trout habitat was restricted in both 2016 and 2017 by warm surface water and anoxic conditions in the hypolimnion (Figure 8). Overall habitat volume was similar in both years, showing a marked decline in available habitat once

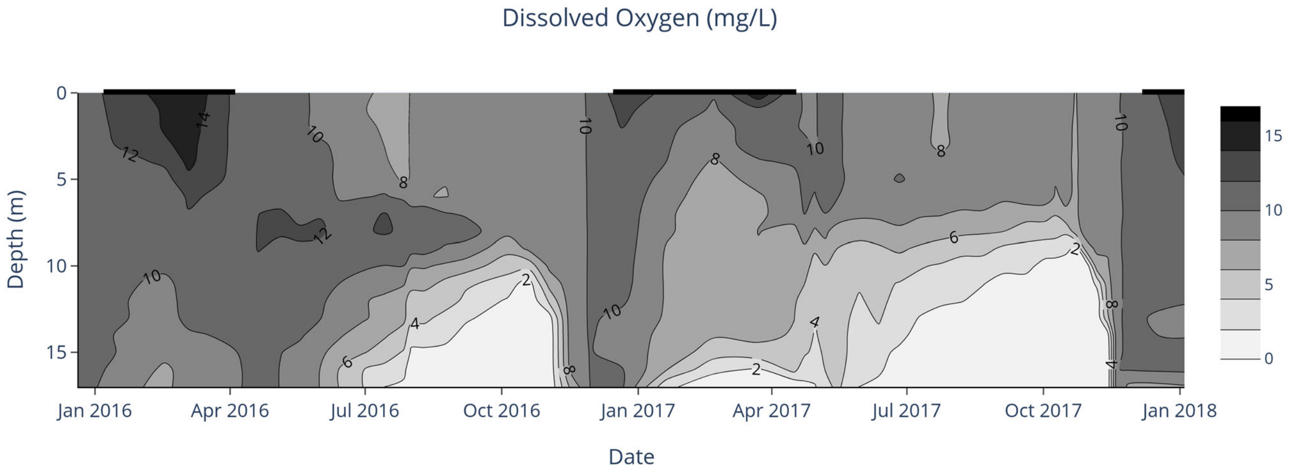

Figure 6. Dissolved oxygen concentrations measured in the Mirror Lake water column. Black bars at the top of the figure indicate periods of ice cover.

Table 1. Historical dissolved oxygen and specific conductance data from previous surveys of Mirror Lake (Lake Placid, NY).

Depth (m)	7 Sep 1954[a]	7 Jul 1967[a]	11 Aug 1971[b]	5 Aug 1974[c]	10 Aug 2001[d]	16 Jun 2003[a]	10 Aug 2016[e]	7 Aug 2017[e]
Dissolved oxygen (mg/L)								
0		10.0	8.7	8.4	8.1		8.1	8.2
1					7.9		8.2	8.3
2					8.0		8.2	8.3
3		8.4			8.1		8.2	8.2
4					8.5		8.2	8.2
5				8.9	10.4		8.2	9.7
6		9.4			12.0		8.0	9.6
7					11.7		11.5	7.5
8			11.2		10.9		11.4	6.4
9	7.8	10.2			7.3		10.9	4.7
10			6.9	7.0	4.0		8.2	3.2
11					3.0		6.9	2.5
12	2.8	8.2			2.0	7.0	4.9	2.1
13					1.1		4.6	0.8
14					0.2		2.8	0.3
15	2.4				0.0		1.7	0.2
16		5.2		0.05	0.0		0.4	0.2
17					0.0	2.0	0.3	0.2
18			1.4					
Specific conductance (μS/cm)								
0				82	158		226	178
1					158		226	178
2					158	216	226	178
3					157		226	178
4					157		226	178
5				88	176		225	198
6					195		225	211
7					217		219	228
8					230		220	252
9					253		221	274
10				92	269		221	285
11					275		222	289
12					279	329	224	291
13					281		226	295
14					285		228	298
15					289		230	301
16				98	297		232	318
17					308		233	326
18								

[a] NYSDEC unpublished data.
[b] Oglesby (1971).
[c] Oglesby and Miller (1974).
[d] UFI (2001).
[e] Current study.

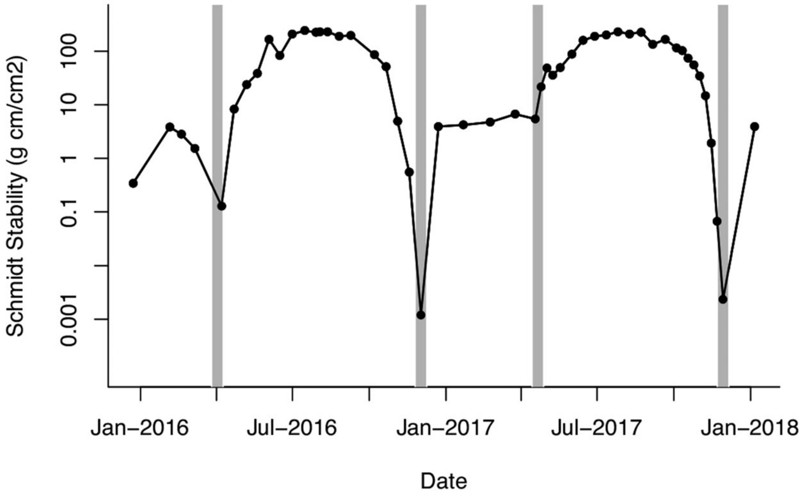

Figure 7. Schmidt stability for Mirror Lake. Gray bars represent expected periods of mixing based on the presence of nearly uniform temperature in the water column.

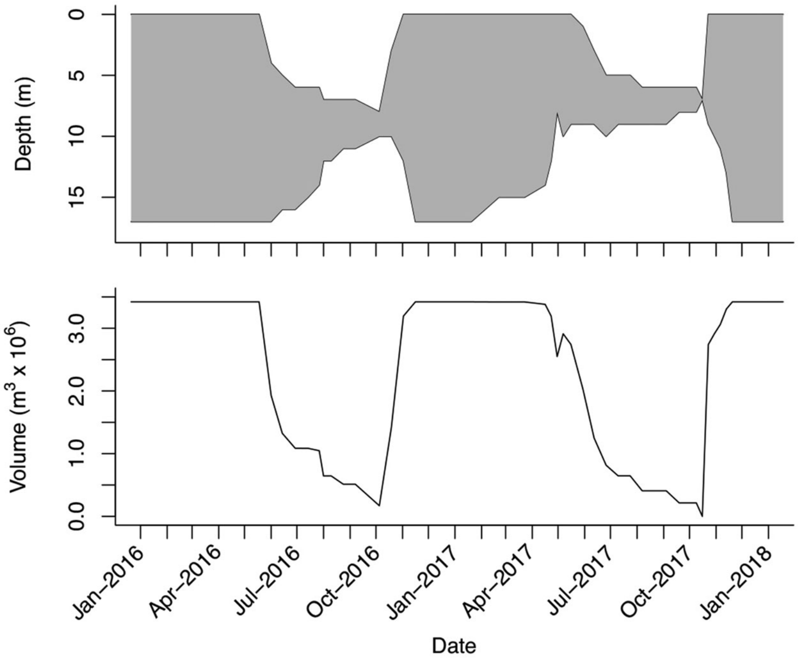

Figure 8. Lake trout habitat area in Mirror Lake (gray shade) as a cross section of the water column in 2016 and 2017 (top panel). Total habitat volume in 2016 and 2017, calculated from habitat suitability in the water column and bathymetric data (bottom panel). Habitat suitability was based on water temperatures less than 15 C and dissolved oxygen concentrations greater than 6 mg/L (Plumb and Blanchfield 2009).

stratification developed. An exception occurred in 2017 when preferred habitat volume briefly reduced to 0 m^3. The greater spatial and temporal extent of anoxia in 2017 was offset by cooler surface water temperatures and a shallower thermocline.

Discussion

Northern temperate lakes of sufficient depth are typically dimictic, turning over twice a year, once in the fall and once in the spring (Wetzel 2001). This is a process critical to the health of a lake, especially one that supports cold stenotherms such as lake trout and rainbow trout. Mirror Lake completely mixed seasonally as expected in all but the spring of 2017. During this period hypolimnetic chloride was much higher than epilimnetic concentrations, resulting in distinct salinity-driven density differences even though the water column was isothermal (Figures 3–5). The

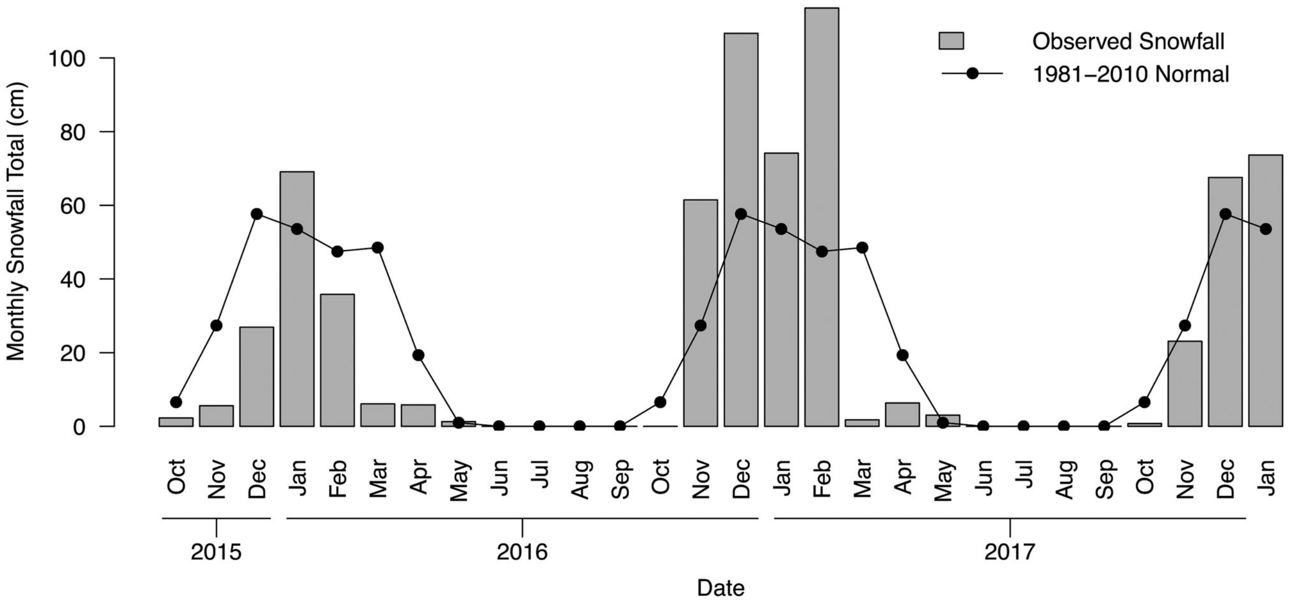

Figure 9. Monthly snowfall in Lake Placid, NY from October 2015 through January 2018. Data pulled from USHCN (Station ID: US1NYES0001).

density gradient due to salinity in the spring of 2017 caused the lake to maintain enough stability to prevent complete mixing of the water column (Figure 7). The persistence of elevated chloride (Figure 4) and low dissolved oxygen (Figure 6) at the lake bottom before and after spring mixing further support this observation.

Twenty-two stormwater outfalls discharge directly into Mirror Lake (Figure 1). These outfalls drain the urban landscape around the lake, including the state road, the village sidewalks, and many parking lots found within the Village of Lake Placid. Discrete sampling of the outfalls during the winter frequently yielded chloride concentrations entering the lake ranging from 500 to 2500 mg/L (Wiltse et al. 2017). These concentrations are 2500 to 12,500 times greater than runoff from least impacted streams in the Adirondack Park (Kelting et al. 2012). The resulting densities for this stormwater range from 1.00085 to 1.00435 g/cm^3, higher than the average density of the lake water at this time (∼1.00000 g/cm^3). The highest concentration and volume of this runoff enter the lake along its western shore, where a steep gradient exists along the lake bottom (Figure 1). The timing of increased chloride concentrations at the lake bottom, density of stormwater, and lake bathymetry together point to a mechanism by which the higher salinity stormwater flows along the lake bottom and accumulates at depth.

Spring mixing in 2016, but not 2017, can be explained by the difference in accumulation of salt at the lake bottom (Figure 4). The winter of 2015–2016 was mild, total snowfall was 152.9 cm, 58% of the 1981–2010 normal of 261.6 cm, and 42% of the 2016–2017 total of 367.0 cm (Figure 9). In the nearby (98 km SSE) Lake George, NY, watershed, a 30–40% reduction in road salt application was observed during the 2015–2016 season (Sutherland et al. 2018). Additionally, several rain events occurred during this winter, diluting stormwater chloride concentrations. With lower chloride in the hypolimnion, lake stability was lower during spring mixing in 2016 as compared to 2017 (Figure 7). Also, ice-off in 2016 was the third earliest in the 114-year ice-record, occurring 25 d earlier than the mean ice-off date (Wiltse and Stager 2018). As a result, the period between ice-off and the establishment of the thermocline in 2016 was 39 d, compared to 7 d in 2017. Therefore, the combination of a lower salt load, dilution from rain events, and prolonged spring mixing allowed for the lake to completely mix in the spring of 2016.

The incomplete mixing in the spring of 2017 resulted in a longer duration and spatial extent of anoxic conditions in the hypolimnion, which have consequences for both the chemistry and biology of the lake. The lack of oxygen in the hypolimnion shifts the redox chemistry, causing mobility of phosphorus, manganese, iron, and other ions from the sediments and particulates in the water column. This has the potential to lead to toxic concentrations of trace metals, sulfide, and ammonia in the hypolimnion, combined with anoxia, which can result in declines in biodiversity as well as fish kills (Wetzel 2001, Koretsky et al. 2012). Prolonged periods of anoxia also may lead to increased internal phosphorus loading in the lake (Wetzel 2001). Precambrian shield lakes, such as Mirror Lake, typically have low rates of internal phosphorus loading, but also tend to be phosphorus limited (Orihel et al. 2017). Therefore, increases in internal phosphorus loading of these lakes can be ecologically significant (Healey and Hendzel 1980, Lean and Pick 1981).

Lake trout are the only native cold-water lake-dwelling top predatory fish in the Adirondack Park (Carlson et al. 2016). Narrow habitat requirements (cold, well-oxygenated water), slow growth, and late sexual maturity make lake trout particularly vulnerable to climate change, eutrophication, and other stressors. In small upland lakes, like Mirror Lake, lake trout habitat is likely to decline with increasing temperatures (De Stasio et al. 1996). Mirror Lake has demonstrated a significant increase in the ice-free period over the past 114 years, with the lake currently experiencing an average of 24 more days being ice-free than in the early 1900s (Wiltse and Stager 2018). Climate-driven effects on the lake trout population in Mirror Lake will be further exacerbated by the lack of complete mixing in the spring.

A simple model of preferred lake trout habitat reveals a constriction in habitat in 2017 when the lake did not completely mix in the spring (Figure 8). It is important to note that conditions outside of the thresholds used here may not be lethal to lake trout. Outside of these values it is likely that the fish are experiencing greater physiological stress, which can have impacts on growth, reproduction, and long-term populations dynamics. Juvenile lake trout appear to have less tolerance for conditions outside of this preferred range of temperature and dissolved oxygen, which could influence recruitment into the population (Evans 2005).

Interannual variability in thermocline depth and long-term changes in lake thermal structure also will play an important role in the volume of suitable habitat. This is evident in the comparison of overall habitat volume between 2016 and 2017. Cooler temperatures and a shallow thermocline in 2017 shifted the suitable habitat up in the water column, providing habitat volumes comparable to those of 2016, despite the lack of mixing. Notably, late-season habitat volume in 2017 dropped to 0 m^3 as fall mixing caused a temporary increase in water temperature at the thermocline and the anoxic zone continued to expand (Figure 8). Conditions in the lake did not become lethal to lake trout during this period, and no fish kill was noted, but greater physiological stress was likely.

The small amount of historical data for Mirror Lake suggests that incomplete mixing is not a natural occurrence for the lake. NYSDEC provided limited data from 7 September 1954 and 7 July 1967. These data show dissolved oxygen concentrations higher than at comparable times of year (2.4 mg/L at 15 m and 5.2 mg/L at 17 m, respectively) in our current data (Table 1, NYSDEC unpublished data). This suggests that Mirror Lake was experiencing greater mixing and/or decreased respiration at depth during those years. Data from NYSDEC on 16 June 2003 show dissolved oxygen concentration at 17 m was 2.0 mg/L, while specific conductance was 216 μS/cm at 2 m and 329 μS/cm at 12 m (Table 1, NYSDEC unpublished data). These data are consistent with our observations during the spring of 2017, when the lake experienced incomplete mixing.

Other historical data suggest that incomplete mixing is a more recent phenomenon for the lake. Surveys of the lake in August 1971 and August 1974 generally found hypolimnetic dissolved oxygen concentrations and specific conductance consistent with greater mixing (Table 1, Oglesby 1971, Oglesby and Mills 1974). Despite the low dissolved oxygen in 1974, specific conductance measurements from that day show a 16 μS/cm difference from the surface to the bottom, indicating that there was little or no chemical stratification. A survey on 10 August 2001 found

0 mg/L of dissolved oxygen at 15 m and a difference in specific conductance from surface to bottom of 150.5 μS/cm, consistent with a lack of spring mixing (Table 1, UFI 2002).

Current and historical data indicate that anoxic conditions are likely normal for Mirror Lake. Natural anoxia is common in relatively shallow lakes where the volume of the hypolimnion is small in relation to the sediment surface area (Fulthorpe and Paloheimo 1985). The lack of spring mixing in Mirror Lake has resulted in an increase in the spatial and temporal extent of the anoxic zone in the hypolimnion, which has the potential to threaten the ability of the lake to support lake trout. Further research should be conducted to study the lake trout population and assess the impact of incomplete mixing. The lake currently is stocked with an average of 450 6–7 inch lake trout annually, but no data are available to assess how long these fish survive in the lake and whether there is natural recruitment in the population.

When the interruption in lake mixing began is difficult to establish. The data available in 2001 and 2003 show elevated conductivity in the hypolimnion during the summer, which is consistent with an accumulation of sodium and chloride, and incomplete spring mixing (Table 1). It is possible that this has been an annual or semiannual occurrence at least since that time period. Unfortunately, the paucity of preimpact data and limited continued monitoring of the lake make it impossible to determine when the lake first experienced incomplete mixing and how frequently it occurs.

We believe that restoration of the lake to dimictic conditions would occur during the spring following a substantial reduction in salt load. The lake has demonstrated an ability to overcome the salt-induced density gradient during fall mixing, and without the establishment of a new gradient the following winter, the lake would mix in the spring. The winter of 2015–2016 offers a glimpse at the restoration potential for the lake. Following a winter with less snowfall and a lower salt load, the lake completely mixed in the spring. Substantial reductions in the application of road salt within the watershed, coupled with stormwater improvements to retain stormwater runoff before entering the lake, would provide marked improvements in the water quality of Mirror Lake.

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