The effects of salinity on the stratification and nutrient dynamics of inland lakes in southeast Michigan

Hallee Kansman

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The effects of salinity on the stratification and nutrient dynamics of inland lakes in southeast Michigan

Abstract
Temperate lakes typically turnover twice annually; however, certain factors can reduce the possibility of turnover. One of these factors may be the addition of road salt to the watershed. Road salt increases the density of water, increasing the energy needed to turnover a lake. Reduced turnover can have major effects on the nutrient dynamics of the lake. In this study, I examined seven small, deep lakes in Southeast Michigan to determine if turnover was affected by salinity. The purpose of this study was to determine whether these turnover events in TSL have changed since 2009 and how common incomplete spring turnover was in other small, deep lakes. I measured the amount of dissolved oxygen, temperature and conductivity and calculated the stability of each lake. I also measured nutrient concentrations and Chl a to determine whether nutrient cycling was affected. One lake, Third Sister Lake (TSL), demonstrated reduced turnover from repeated years of salt inputs.

The results of this study indicate that incomplete spring turnover occurred in two lakes: Third Sister Lake and Pickerel Lake, although excessive salt accumulation only occurred in TSL, suggesting that other factors may have caused this same phenomenon in Pickerel Lake. I found that these two lakes were also the most stable. In TSL, phosphorus was trapped in the hypolimnion during the summer and Chl was highest in the metalimnion. However, we did not see these patterns in Pickerel Lake. Lower nutrient and oxygen availability creates unfavorable conditions for the wildlife of each lake. Other lakes, such as Pickerel Lake, that experienced decreased turnover should be monitored as they could follow the same fate as TSL if ever salt were presented into that particular watershed.

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Subject Categories
Biology

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THE EFFECTS OF SALINITY ON THE STRATIFICATION AND NUTRIENT DYNAMICS OF INLAND LAKES IN SOUTHEAST MICHIGAN

By

Hallee Kansman

A Senior Thesis Submitted to the

Eastern Michigan University

Honors College

in Partial Fulfillment of the Requirements for Graduation

with Honors in Biology

Approved at Ypsilanti, Michigan, on this date Dec. 4, 2015
The effects of salinity on the turnover in small, deep lakes of SE Michigan

Abstract

Temperate lakes typically turnover twice annually; however, certain factors can reduce the possibility of turnover. One of these factors may be the addition of road salt to the watershed. Road salt increases the density of water, increasing the energy needed to turnover a lake. Reduced turnover can have major effects on the nutrient dynamics of the lake. In this study, I examined seven small, deep lakes in Southeast Michigan to determine if turnover was affected by salinity. The purpose of this study was to determine whether these turnover events in TSL have changed since 2009 and how common incomplete spring turnover was in other small, deep lakes. I measured the amount of dissolved oxygen, temperature and conductivity and calculated the stability of each lake. I also measured nutrient concentrations and Chl a to determine whether nutrient cycling was affected. One lake, Third Sister Lake (TSL), demonstrated reduced turnover from repeated years of salt inputs.

The results of this study indicate that incomplete spring turnover occurred in two lakes: Third Sister Lake and Pickerel Lake, although excessive salt accumulation only occurred in TSL, suggesting that other factors may have caused this same phenomenon in Pickerel Lake. I found that these two lakes were also the most stable. In TSL, phosphorus was trapped in the hypolimnion during the summer and Chl was highest in the metalimnion. However, we did not see these patterns in Pickerel Lake. Lower nutrient and oxygen availability creates unfavorable conditions for the wildlife of each lake. Other lakes, such as Pickerel Lake, that experienced decreased turnover should be monitored as they could follow the same fate as TSL if ever salt were presented into that particular watershed.
The effects of salinity on the turnover in small, deep lakes of SE Michigan

Introduction

Aquatic ecosystems face a number of different environmental stressors, which stem primarily from human population growth and increases in land use and hydrology (Verdonschot, et. al. 2012). Observational studies show that nutrient inputs, climate change, contaminants, water withdrawal, habitat degradation and salinity can play large roles in the alterations of lake ecosystems (Norton et al., 2015). These stressors can impact aquatic ecosystem structure, e.g., stratification patterns or species composition, and function, e.g., primary productivity. For example, increases in impervious surfaces correlate to temperature spikes, increased toxic substances, decreased dissolved oxygen and increased salinity (Verdonschot, et. al. 2012). One way to evaluate impacts of stressors is to compare stressor levels at impacted sites of to stressor levels at comparison sites that are unimpaired or less degraded (Verdonschot, et. al. 2013).

One stressor that can affect the aquatic structure and function is an increase in salinity due to road salt run-off. Road salt has been used since the 1950s to aid in snow and ice removal in the United States (Godwin et. al., 2002). Although beneficial in creating safe road conditions, salt can have negative effects on ecosystems, including the aquatic ecosystems such as ponds, lakes and rivers. Salt lowers the freezing point of water causing ice to melt, insuring safe driving conditions. When water runs off treated roads, dissolved road salt washes into nearby ponds and streams (Schlesinger & Findley, 2009). The runoff can create higher salinity levels in lakes, affecting the species richness and composition (Williams et. al. 1990). The
The effects of salinity on the turnover in small, deep lakes of SE Michigan runoff and increased salinity can also increase the density of water. Because salt lowers the freezing point, salt also can cause lakes to remain unfrozen for longer periods during the winter.

Driven by an increased public expectation for safe and clear roads, and fueled by relatively low costs, Michigan has steadily increased its use of road salt over the last 30 years (Road Salt Pricing Report). Deicing agents, such as road salt, are transported as solutes into adjacent habitats where they influence biotic and abiotic aspects of the environment (Karraker et. al., 2008). Transportation departments apply deicing agents seasonally to roads in 26 states in the United States (National Research Council 1991).

The addition of salt to lakes increases the water density, which affects lake stability and turnover. The typical mixing pattern of temperate lakes is that turnover occurs in the spring and fall seasons, when the dense layers from the bottom and lighter layers from the top mix. Salt inputs cause the density difference between the epilimnion and the hypolimnion to increase, requiring more energy to cause turnover. Without mixing, a highly saline lake can become anoxic, which can affect the species richness and composition within the aquatic ecosystem. If temperature and wind forces cannot overcome the greater difference in the water density, then the lake will not turnover.

In the summer, lakes stratify when surface waters warm and become less dense than the underlying cooler bottom waters. Once stratification occurs, there is very little mixing between the upper two layers. The surface layer is called the epilimnion, while the bottom layer is called the hypolimnion. The thin middle layer,
The effects of salinity on the turnover in small, deep lakes of SE Michigan which is the plane where temperature is rapidly changing, is called the metalimnion. When a lake stratifies, phytoplankton consume nutrients and produce oxygen in the upper waters while in the bottom waters, microorganisms in the sediments consume oxygen as they respire remineralized dead organic matter, which releases nutrients. Fish and other organisms, including phytoplankton, zooplankton, and microbes, depend on mixing to redistribute nutrients and oxygen (Wetzel & Likens, 2000; Bronmark & Hansson, 2005) and so, a highly saline lake may not provide a proper environment for the organisms within it if it cannot turnover effectively.

Changes in lake turnover dynamics could affect nutrient availability and primary production. Seasonal patterns in stratification and turnover can impact nutrient availability and primary production. Within a stratified lake, nutrients accumulate in the bottom layer, due to decomposition in lake sediments, while oxygen concentrations are higher in the epilimnion. The surface layer receives inputs of oxygen from the atmosphere and photosynthesis, while, the bottom layer has no direct input of oxygen, and oxygen is consumed during respiration due to the decomposition of dead organic material that falls to the bottom of the lake. In the surface layer, nutrients inputs may come from tributaries and runoff, while uptake by phytoplankton removes nutrients. In the bottom layer, nutrients increase due to remineralization of dead organic material. Most lakes will undergo spring and fall turnover events, which resupply bottom waters with oxygen and surface waters with nutrients to fuel primary production (Figure 1). Lack of turnover can deteriorate the water quality, increasing the turbidity and nutrients within a
The effects of salinity on the turnover in small, deep lakes of SE Michigan particular lake. This process is called eutrophication. With an increase in nutrients, the lake will become more turbid, thus decreasing the primary productivity.

Figure 1: Conceptual diagram illustrating the effects of seasonal turnover within inland lakes, indicating high oxygen in the epilimnion and high nutrients in the hypolimnion during stratification (Pearson 2008).

The larger the difference in density between the epilimnion and hypolimnion, the more energy it takes for turnover to occur, which in turn affects the stability. Stability refers to how much energy is needed to result in turnover. Lakes can also be categorized by the amount of mixing that occurs per season. Meromictic lakes do not turn over each season, whereas a dimictic lake mixes at least twice a year.

There are several factors that can affect the likelihood of mixing. Wind is one factor, and deep lakes require more wind energy to mix completely. If salts have accumulated in the bottom waters, more energy is required for turnover to occur (Wetzel & Likens, 2000). Third Sister Lake (TSL) is a local lake with reduced turnover owing to very high salinity (Bridgeman et al., 2000; Judd et al., 2005). Third Sister Lake, which is located west of Ann Arbor, MI, is a meromictic lake. This
The effects of salinity on the turnover in small, deep lakes of SE Michigan is different from a dimictic lake, which mixes at least twice a year, which is typical in this climate. Monitoring meromictic lakes would alert us as to whether changes are occurring that could be the result of human inputs that may be avoidable (Denys, 2009).

Third Sister Lake is a small, deep kettle lake located in the Saginaw Forest and owned by the University of Michigan. Its watershed is not heavily urbanized, which suggests that other small deep lakes may also be affected. Previous studies on lakes in southeast Michigan have found that other lakes may experience incomplete turnover in the spring (Denys, 2009;). In a study that analyzed the planktonic biomass of five small, deep lakes in southeast Michigan, Denys (2009) found that each lake displayed different degrees of spring turnover. Third Sister Lake has had a decreased number of occurrences in which the lake has turned over in the spring and fall. The salinity of Third Sister Lake has been increasing, causing a higher density of the bottom water layer and possibly resulting in a reduced ability to mix (Bridgeman et al., 2000; Judd et al., 2005).

**Table 1**: Prediction of how what would be present in the top and bottom layers of lakes with or without excess salt buildup. “Weak” and “Strong” denotes the amount of salt influence within the lake. Complete and minimal mixing refers to the amount of stratification.

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td><strong>Spring</strong></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Complete mixing (weak)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hypolim.</td>
<td>Nutrients</td>
<td></td>
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<td></td>
</tr>
<tr>
<td><strong>Minimal mixing (strong)</strong></td>
<td></td>
<td>Nutrients</td>
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<td><strong>Spring</strong></td>
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<tr>
<td>Complete mixing (weak)</td>
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<tr>
<td><strong>Minimal mixing (strong)</strong></td>
<td></td>
<td>Nutrients</td>
<td></td>
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<tr>
<td><strong>Late Sum.</strong></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Epilim.</td>
<td>Primary Production</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hypolim.</td>
<td>Nutrients</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Late Sum.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Epilim.</td>
<td>Nutrients (very low prim. prod.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hypolim.</td>
<td>Nutrients</td>
<td></td>
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</tr>
</tbody>
</table>
In this study I addressed the following questions: How common is incomplete spring mixing in small deep lakes in Southeast Michigan?; are the mixing patterns observed in 2015 similar to those observed in 2009?; and how are nutrient and phytoplankton dynamics related to spring turnover? I hypothesized if salt accumulating in bottom waters increases lake stability, then I will find reduced mixing in deeper, protected lakes in the spring. Also, if a lake does not completely turnover in the spring, then oxygen and nutrient levels will not mix between the layers and primary productivity may decrease, especially later in the summer. More stratified lakes, such as TSL, will have fewer nutrients in the spring than lakes that are less stratified because of reduced spring mixing. Based on their morphometry, I predicted that in the spring, nutrients would be higher in Bruin Lake and South Lake, which have lower conductivity in their bottom waters and are expected to mix. Chlorophyll concentrations were expected to directly relate to nutrient availability. In order to test these hypotheses, seven lakes were sampled at various depths. Different variables such as temperature, conductivity, pH and oxygen levels were measured.
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**Materials and Methods**

**Study Sites:**

Seven lakes were selected for this project based off of location and depth. I collected water samples, during August 2014, from four lakes of similar depths (at least 15m in depth) in SE Michigan: Third Sister Lake, South Lake, Pickerel Lake and Bruin Lake, and added three additional lakes, North Lake, Blind Lake and Half Moon Lake in May and August of 2015. Lakes differed in size and volume, but had similar depths (Table 2). Samples were taken between May 5th and 14th for the spring session of 2015 and between July 27th and August 3rd for the summer session of 2015.

**Table 2:** Lake depth, volume and area; Half–Moon Lake has both the greatest volume and area; TSL and Pickerel have smallest overall area.

<table>
<thead>
<tr>
<th>Lake</th>
<th>Max Depth (m)</th>
<th>Volume (L)</th>
<th>Area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Third Sister</td>
<td>19</td>
<td>301,180</td>
<td>42,610</td>
</tr>
<tr>
<td>South</td>
<td>25.9</td>
<td>1,070,151</td>
<td>914,754</td>
</tr>
<tr>
<td>Pickerel</td>
<td>16.7</td>
<td>119,505</td>
<td>84,898</td>
</tr>
<tr>
<td>Bruin</td>
<td>15.2</td>
<td>2,798,339</td>
<td>618,678</td>
</tr>
<tr>
<td>North</td>
<td>16.7</td>
<td>1,203,873</td>
<td>1,013,609</td>
</tr>
<tr>
<td>Half Moon</td>
<td>25.9</td>
<td>11,873,691</td>
<td>1,423,195</td>
</tr>
<tr>
<td>Blind</td>
<td>22.8</td>
<td>2,447,825</td>
<td>357,590</td>
</tr>
</tbody>
</table>
Field Sampling:

Measurements for percent dissolved oxygen (DO), conductivity, pH, and temperature were taken at one to two meter intervals at the deepest point using an YSI model 6600 Sonde. The position of the metalimnion was determined from temperature and oxygen readings. Samples for water chemistry and Chlorophyll α analysis were taken from the epilimnion and metalimnion layers of the lake with a Kemmerer sampler. The sample from the Kemmerer was immediately transferred into acid-washed dark 1L Nalgene bottles, stored on ice, and returned to the lab for filtering through glass fiber filters (GF/F). Filtered water used for chlorophyll analysis was stored in the freezer until nutrient analysis. Visibility of the water was accounted for by taking a Secci depth.

Chlorophyll α Analysis:

Phytoplankton biomass was estimated by measuring chlorophyll α (Bronmark and Hansson 2005). Chlorophyll α is the main pigment that photosynthetic organisms use to photosynthesize; its absorbance can be measured at a certain wavelength that excludes other chlorophylls and reflects the amount of active photosynthesizing phytoplankton in the sample (Wetzel & Likens, 2000). In a dim room, to prevent any chlorophyll breakdown, the filters containing the phytoplankton were lysed to extract the chlorophyll by placing the filter in a
The effects of salinity on the turnover in small, deep lakes of SE Michigan polypolypropylene centrifuge tube and adding 5mL of 90 percent ethanol alcohol per tube. Tubes were then placed in a pre-heated 80 degree Celsius bath for 5 minutes and refrigerated overnight. Any samples that lost too much ethanol received just enough to get back to the original 5mL volume. The tubes were mixed using a centrifuge for roughly 5 minutes. Each sample was pipetted into a cuvette that would be placed in a spectrophotometer. The absorbance of each sample was measured at both 665nm and 750nm wavelengths. They were then acidified with 0.05 mL of HCl, and the absorbance re-measured at each wavelength to isolate active chlorophyll from the non-functional chlorophyll. The equation for chlorophyll concentration (\( \mu \text{g L}^{-1} \) = \((\text{Abs}_{665} - \text{Abs}_{750}) \times 28.66 \times V) \) for volume of EtOH (Sartory & Grobelaar, 1984), was used to determine the concentration of chlorophyll to biomass ratio dependent upon nutrient content and light exposure. If the absorbance at 665nm was too high, the sample was diluted by adding 90% EtOH and re-read; if the absorbance at 750 nm was too high, samples were re-centrifuged and re-read (Francoeur et al., 2013).

**Nutrient Analysis:**

After collection, the water samples were used for both quantitative pigment analysis and phosphorus (P) concentration analysis (Wetzel & Likens, 2000). In freshwater lakes, P is often found to be the growth-limiting nutrient, because it occurs in the least amount relative to the needs of plants (Murphy, 2007). A series of different reagents were made up including phenolphthalein indicator, sulfuric acid solution, ammonium molybdate, potassium antimonyl tartrate, ascorbic acid
The effects of salinity on the turnover in small, deep lakes of SE Michigan

solution, strong acid solution, mixed reagent (combination of potassium antimonyl tartrate solution, sulfuric acid solution and ascorbic acid solution), stock phosphorus solution and standard solution. For the standard solution preparation, different volumes (100µg, 50µg, 30µg, 10µg, 5µg and 0µg L⁻¹ P-PO₄³⁻) were pipetted into volumetric flasks in order to create a comparable control standard curve. The mixed reagent was then added to the standard solutions and the twelve lake samples that were collected previously. If P was present the solution would turn a blue color in proportion to the amount of P it contained. After about ten minutes, each sample was run through the spectrophotometer in order to measure the absorbance. Three replicates were used for both the twelve sample bottles and the six standard solutions giving a total of 54 for the entire analysis. The equation for P concentration, µg L⁻¹ = (sample abs) x (slope) + (intercept) was used in order to determine the full concentration available within each lake sample depth (Lind, 1985).

Lake Stability:

In order to determine stability, the area of each layer (epilimnion and hypolimnion) of the lake was determined; this was done by cutting out each layer from a bathymetric map and comparing the weight to a square of known area (using the map legend). These values were then placed in the equation: (Area of square paper cutout/weight of the square paper cutout) x (weight of lake shape cutout) in order to get the area of each layer. Using the area of the top and bottom of a layer, I found the volume of that specific layer with the equation for a truncated cone below.
The effects of salinity on the turnover in small, deep lakes of SE Michigan

\[ V = \frac{h(A_{top} + A_{bot} + \sqrt{A_{top} \times A_{bot}})}{3} \]

Once the volume of each layer was found, I added them together for the total volume of the entire lake. Using the volume, the area of each lake was calculated:

\[ \text{volume} = \text{area (top and bottom)} \times \text{thickness of summed layers (1-2m)}. \]

I calculated this in both Spring and Summer 2015 for each lake.

To obtain the water density for each layer of the lake, I used an online density calculator that required the temperature and conductivity readings from each layer of each lake (http://www.hbuehrer.ch/Rechner/H20density.html). Multiply the proportion of total volume by the density for each layer and use those values to find the average density of the lake. Finally, to get the overall stability of the lakes I multiplied: (the depth at the center of each layer) by (the average density of that proportion of volume) by (the surface area). This resulted in a stability calculation in units of cmg/cm².

**Results**

2014 Summer Trial:

In August 2014, there was higher chlorophyll in the metalimnion of Third Sister Lake and the hypolimnion of Bruin Lake (Figure 2). The variables of temperature (Figure 4), pH (Figure 6), and dissolved oxygen (Figure 3) all decreased with increased depth for each lake. Third Sister Lake showed the highest amount of conductivity, which correlates to its increased salinity (Figure 5). It also has a larger drop in dissolved oxygen levels as compared to the other lakes,
The effects of salinity on the turnover in small, deep lakes of SE Michigan illustrating how the lake barely turns over, leading to decreased overall levels of oxygen in the hypolimnion (Figure 3).

**Figure 2:** Biomass of phytoplankton illustrated by chlorophyll a concentrations: more primary production seen within the metalimnion of Third Sister Lake and the hypolimnion of Bruin Lake.

**Figure 3:** Percent Dissolved oxygen represented in all four lakes sampled: greater drop in dissolved oxygen seen at earlier depth in Third Sister Lake.
The effects of salinity on the turnover in small, deep lakes of SE Michigan

![Temperature vs. Depth Graph](image1)

**Figure 4:** Temperature changes with depth (Summer 2014).

![Conductivity vs. Depth Graph](image2)

**Figure 5:** Conductivity changes with depth (Summer 2014).
The effects of salinity on the turnover in small, deep lakes of SE Michigan

Figure 6: pH trends with depth (Summer 2014).

2015 Spring and Summer Trials

Depth profiles:

The depth profiles in Third Sister and Pickerel Lake indicating that these lakes did not turnover completely in the spring (Fig. 8 & Fig. 11). Third Sister Lake showed a more substantial decrease in oxygen than any other lake during the spring (Fig. 9). Third Sister Lake also had the highest conductivity in the bottom waters in the spring (Fig. 10). During the summer, both Third Sister and Pickerel Lake had the lowest oxygen levels in both the surface and bottom waters (Fig. 12). Third Sister Lake again had the highest conductivity in the summer (Fig. 13). Half Moon and Pickerel Lake also had relatively high conductivity readings (Fig. 13).
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**Figure 8:** 2015 Spring Temperature Readings. TSL showed extreme, rapid, drop-off in temperature from surface to about 5 degrees Celsius.

**Figure 9:** 2015 Spring Dissolved Oxygen Levels. TSL has rapid decrease in amount of oxygen in epilimnion as density increases due to salt accumulation.
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Figure 10: 2015 Spring Conductivity Reading. TSL with apparent trend of increased conductivity with depth; starting at even higher initial salinity levels compared to the other lakes.

Figure 11: 2015 Summer Temperature Readings. Pickerel Lake demonstrated rapid decrease in temperature with increased depth.
The effects of salinity on the turnover in small, deep lakes of SE Michigan

**Figure 12:** 2015 Summer Dissolved Oxygen Levels.

**Figure 13:** 2015 Summer Conductivity.
The effects of salinity on the turnover in small, deep lakes of SE Michigan

Chlorophyll:

There was a general pattern in the spring for higher chlorophyll in the hypolimnion, while in the summer, the higher amounts of chlorophyll were found in the epilimnion (Fig. 14 & 15). Third Sister Lake displayed an atypical pattern: higher chlorophyll in the hypolimnion during the summer trial (Fig. 15).

**Figure 14:** 2015 Biomass of phytoplankton expressed by chlorophyll a concentrations: Overall lower levels of primary productivity in the spring month as compared to summer months.
The effects of salinity on the turnover in small, deep lakes of SE Michigan

![Graph: Average Chlorophyll a (mg/l) for Summer 2015 in different lakes]

**Figure 15:** 2015 Biomass of phytoplankton expressed as chlorophyll a concentrations: Higher primary production in metalimnion of TSL; all other lakes displayed common trend of increased primary production in epilimnion during summer months.

**Nutrients:**

Half Moon Lake had the highest overall nutrient reading in the hypolimnion during the summer (Fig. 17). In the spring trial (Fig. 16), practically every individual layer was accounted for in terms of nutrient accumulation as the lakes mix.

**Stability:**

Every lake showcased an increase in stability from the spring to summer trial (Table 3). During the spring, stability was ranked as Pickerel had the greatest amount of stability, followed by Third Sister, Half-moon, Bruin, South and North Lake having the lowest overall stability. This order remained the same for the summer stabilities. Pickerel and Third Sister Lake had the highest overall stabilities for both seasons (Table 3).
The effects of salinity on the turnover in small, deep lakes of SE Michigan

**Spring 2015**

![Spring 2015 graph with PHOS graph](image)

**Figure 16:** 2015 Phosphorus concentrations; higher amounts of nutrients seen within the hypolimnion of TSL and Half-Moon Lake. *Data was collected for every lake, however some points were too small to detect and so were given a value of 0.001.

**Summer 2015**

![Summer 2015 graph with PHOS graph](image)

**Figure 17:** 2015 Phosphorus concentrations; higher amounts of nutrients seen within hypolimnion of Half-Moon Lake and TSL, very small amounts witnessed in Bruin Lake. *Data was collected for every lake, however some points were too small to detect and so were given a value of 0.001.
The effects of salinity on the turnover in small, deep lakes of SE Michigan

Table 3: General increase in stability from spring to summer 2015 as layers settle in summer.

<table>
<thead>
<tr>
<th>Lake</th>
<th>Bruin</th>
<th>Half Moon</th>
<th>North</th>
<th>Pickerel</th>
<th>South</th>
<th>Third Sister</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spring 2015</td>
<td>0.2739</td>
<td>0.3586</td>
<td>0.0384</td>
<td>0.8819</td>
<td>0.2702</td>
<td>0.7346</td>
</tr>
<tr>
<td>Stability:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer 2015</td>
<td>0.5103</td>
<td>1.0175</td>
<td>0.1253</td>
<td>2.9724</td>
<td>0.5097</td>
<td>2.6950</td>
</tr>
</tbody>
</table>

Discussion

Turnover, stability and nutrients levels:

The results from the lake measurements indicate that increased salinity resulted in incomplete turnover in only Third Sister Lake, however, another lake (Pickerel) also showed signs of reduced turnover, suggesting that other factors may also reduce turnover. The high conductivity in the bottom waters of Third Sister Lake resulted in decreased mixing during the spring and increased stability during the spring and summer. TSL was more stratified than the other lakes in the spring months and thus was predicted to have lower nutrient levels in the epilimnion, especially later in the summer, and this is what was observed (Figure 17).

Conductivity is a proxy for salt concentration. TSL had a very high conductivity value during both seasons and both years sampled, even increasing with depth as salt sank to the bottom, accumulating with each year. Half-Moon Lake also had higher conductivity in the summer, but since conductivity was low in the spring, it is not clear what caused the increase. Overall, in the spring, Third Sister and Pickerel Lake had an increased stability and decreased mixing.
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Oxygen availability affects the biota and biogeochemical processes. Both summer trials show a general decrease in dissolved oxygen with depth. As less oxygen becomes available in the bottom waters, the environment transitions to one that may be unsuitable for existing organisms. This may be especially prevalent in TSL as oxygen is depleted, fewer nutrients are available, and therefore abundance of bottom-dwelling organisms declines. Other lakes would not demonstrate this competition for oxygen and nutrients as compared to lakes such as TSL and Pickerel that display reduced turnover.

Anoxic conditions are created in lakes that demonstrate minimal mixing. Higher phytoplankton production was found in the hypolimnion rather than the epilimnion in Third Sister and Half-Moon, decreasing the amount of oxygen available at the surface waters, therefore creating anoxic conditions. Such continuance of conditions may create an unfavorable environment to the wildlife inhabiting the lake.

All seven lakes saw an increase in stability from spring to summer, which was expected as stratification becomes stronger. Third Sister and Pickerel both had very high stability readings (0.8819 to 2.972 in Pickerel and 0.7346 to 2.695 in TSL) as compared to North Lake, which had the lowest readings (from 0.0384 to 0.1253), demonstrating how much more energy is required for turnover in TSL and Pickerel. Salt is definitely the determining factor for reduced turnover in TSL, however, it is not the case for Pickerel Lake since the conductivity readings were not very high. The cause may simply be due to the fact Pickerel is a small, deep and a relatively cold lake. The cooler water also increases the density of the lake and
The effects of salinity on the turnover in small, deep lakes of SE Michigan thus requires more energy to turnover. It is interesting that TSL is not that much more stable than all the other lakes, since it has such a high conductivity. In fact, Pickerel Lake is more stable.

Incomplete spring mixing in small deep lakes is influenced by the accumulation of salts in the bottom waters, as seen in lakes such as Third Sister and Half-Moon Lake. Of the lakes we surveyed, only Third Sister Lake appears to be strongly affected by increased salinity that turns over minimally or not at all. The display of higher amounts of nutrients in the hypolimnion of TSL in both the spring and summer months and of chlorophyll in the bottom waters aids in the prediction of incomplete turnover influenced by increased conductivity with depth. It may be that Pickerel and Half Moon Lake do not turn over every spring.

My findings, compared to the 2009 analysis of incomplete spring turnover (Denys, 2009), are very similar. I propose that other factors beside salt, such as the depth and small surface area, may be affecting the inability of Third Sister to turnover. However, I did test the possibility of how size and shape would affect the rate of turnover by sampling North Lake (1,013,609 m² in area), which is relatively large compared to the other four lakes, which had lower stability. The smaller lakes: Third Sister, Pickerel and Half-Moon, had the highest stability and highest conductivity. The higher levels of nutrients in the hypolimnion of Third Sister, Half-Moon and Pickerel Lake coincide with the depleting oxygen levels, indicating a decrease in mixing.
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Road Salt:

The most likely source of salt in lakes is from road salt application. Salt inputs affect the stability of the lake, creating anoxic conditions. In winter of 2014, Washtenaw County used about 22,500 tons of salt (Figure 18).

![ANNUAL SALT USAGE (Seasonal)](image)

**Figure 18:** Road Salt Usage from 2007-2015; highest amounts of salt used in '07-08 and '13-14 winters.

The prices for salt have increased at least 20% since 2013 in Michigan, and the demand has increased as the winters have become harsher (North American Salt Company). Washtenaw County reported a 46% and 122% price hike in 2014 for early and seasonal fills, respectively (Road Salt Pricing Report), using nearly 2 million tons of salt annually to clear snow and ice (Road Salt Pricing Report). With 14 salt deposits in Michigan alone, our state runs the risk of increased pollution of our waters due to salt. Although Third Sister Lake is secluded from any major roads,
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the road salt could be seeping into the lake via runoff from a nearby parking lot. The increased amount of salt will only hinder the lakes ability to turnover.

Other studies have documented the impacts of road-salt on aquatic biota. Salt also can have adverse effects on the biota of the lake ecosystem. Some species are more tolerant to anoxic conditions, while others would struggle in the “oxygen less” environment. The amount of diversity of different species in a lake may indicate the health of the lake, as well as providing a useful history to indicate whether species are becoming extirpated from a particular lake.

Haloclines of small, deep lakes:

In addition to road salt affecting lake turnover dynamics, the mechanics of a lake’s halocline may just be as important. The halocline is a layer separated by the levels of salt, generally possessing greater amounts of salt in the above layer. Haloclines are often present in oceans, which have high levels of salt naturally. However, lakes that are deep enough and influenced by high levels of salt can have distinguished layers as seen in Third Sister Lake. The size and depth of the lake, which are determined by basin geology, allow for specific layers to form. The Michigan Basin is a simple, essentially undeformed cratonic basin influenced by tectonic activity (Howell & Van Der Pluijm, 1990). The basin was completely overrun by ice sheets during at least the last three glacial events, as evidenced by remnant glacial deposits (McIntosh, 2010).

The geology of the basin may also contribute to slat inputs. Glacial events caused salt deposits in the bedrock. Glacial melt waters penetrated hundreds of
The effects of salinity on the turnover in small, deep lakes of SE Michigan meters into the underlying sedimentary basins and fractured crystalline bedrock, disrupting relatively stagnant saline fluids and creating a strong disequilibrium pattern in the fluid salinity (McIntosh, 2010). Despite the presence of dense brines, glaciation was still able to reorganize salinity gradients and drive basin scale fluid migration (McIntosh, 2010). Because of its depth, defined by the morphology of the basin, TSL may continue to intercept saline fluids in the bedrock. However, the salinity of the lake did not begin to increase until the nineteen eighties (Bridgeman et al. 2000), suggesting that road salt inputs are the main cause of the accumulation of salt in the bottom waters.

Future studies should concentrate on the effects of groundwater on the salt composition of small deep lakes, such as Third Sister. If runoff causes road salt to seep into rivers and streams, eventually leading to lakes, the groundwater would be tainted and therefore increase the salt levels in these lakes. Other studies should also evaluate the geology of the bedrock near Third Sister Lake. According to the figure (Fig. 19) below, Washtenaw County is comprised of shale from the Mississippian subperiod of the Devonian period.
Figure 19: MI Bedrock Geology. Washtenaw County comprised of mainly coldwater shale.
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By highlighting the bedrock, we can describe the history of small deep lakes in Washtenaw County and how glacial water may have affected the salinity in each lake.

Effects of Turnover on Biota:

There is a lot of data on the fish populations in TSL. The fish of TSL were removed by angling, netting and the use of rotenone (Brown & Ball, 2011). The populations were then recovered by handpicking. Legal game fish make up approximately 70% of the total weight in TSL, with Bluegill and Large mouth bass making up a fourth of the population. Recently, records indicate about 15,454 fish inhabit Third Sister Lake after the introduction of the poison (Brown & Ball, 2011). There is a chance that these fish are already acclimated to the higher salinity in the lake since the population has not necessarily decreased. The main impact of salt on lake biota is likely through its impacts on reducing oxygen in the bottom waters.

If salt is not a determining factor for fish survival, then it is interesting to notice how other small, deep lakes have had problems with turnover affecting biota. Similar to TSL, Half-Moon also experienced decreased turnover. Records from this lake illustrate a history of anglers catching bluegill, crappie and large mouth bass (Herman, 1992). Although both lakes had a history of species removal, the relationship between increased salinity and biota depletion is not showcased. Analyzing the species present in a lake will aid in determining the turnover rate.
Conclusion:

This study found it is not uncommon for small deep lakes to have reduced turnover in the spring. Third Sister is indeed an unusual lake in it has not turned over in at least a decade. We can conclude, with the help from previous studies, Third Sister has experienced very few spring mixing events. Findings from TSL could suggest that other lakes follow the same fate, especially if it is a small, deep, protected lake.

With an increased salinity, the density of the lake increases and thus decreases the frequency of turnover. Lack of turnover in the spring in these temperate, freshwater lakes could be a part of normal fluctuations over a longer time frame or they could be indicative of human influences due to increasing human population growth (Denys, 2009). Globally people withdrawal 50 percent of all the available freshwater according to a 1998 study (Bronmark & Hansson, 2005); this demand will increase as the population continues to grow. Increasing populations also give rise to pollutants affecting water quality, such as through the use of pesticides and fertilizers. Past efforts in the state have focused on emphasizing the importance of regularly monitoring Southeastern Michigan Lakes to maintain the freshwater ecosystems (Fuller & Minnerick, 2008). My findings not only support, but also accentuate the continued monitoring detailed by the previous study (Fuller & Minnerick, 2008). It is our job as humans to protect the resources around us from misuse; understanding lake dynamics is only the beginning.
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References:


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