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# Effects of road salt deicers on an urban groundwater-fed kettle lake

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ABSTRACT

Road salt deicers significantly influence the chemistry and physical mixing of urban lakes, even causing transition from dimixis to monomixis or meromixis. In this study, the water column geochemistry of Asylum Lake, a primarily groundwater-fed, eutrophic kettle lake in urban Kalamazoo, MI, was monitored for over a year to determine the extent of road salt deicer influence on the lake chemistry and the physical mixing of the lake. Water column samples from the surface to the deepest part of Asylum Lake were analyzed monthly for nineteen months for a suite of parameters including dissolved oxygen, pH, conductivity, temperature, alkalinity, $Fe^{2+}$, $Mn^{2+}$, orthophosphate, total $NH_4^+$, alkalinity, total sulfide, $Cl^-$, $SO_4^{2-}$, $Ca^{2+}$, $Mg^{2+}$, $K^+$, and $Na^+$. During the study period, spring mixing was never observed and a nearly complete fall turnover was observed only in November 2013. The hypolimnion of Asylum Lake was always hypoxic or anoxic and redox-stratified, with seasonal development of suboxic and sulfidic zones, which were disrupted in fall and winter following partial fall turnover and subsequent ice cover. This study suggests that road salt deicers have caused Asylum Lake to transition from dimixis to meromixis or periodic monomixis with significant consequences for biogeochemical cycles in the lake waters.

## 1. Introduction

The widespread application of road salt deicers has the potential to significantly influence the salinity of freshwater systems. In the United States, an estimated 8 Mt of salt was used for deicing in 1975, increasing to 55 Mt in 2003 (U.S. Geological Survey, 2014). Rising chloride levels related to the use of road salts have been documented in groundwater and surface waters in the United States, Canada and elsewhere (e.g. Environment Canada, 2001; Chapra et al., 2009, 2012; Mullaney et al., 2009; Kaushal et al., 2014; Rogora et al., 2015; Dugan et al., 2017). For example, Novotny et al. (2008) showed that urban lakes in Minnesota have 10 to 25 times greater sodium and chloride levels as compared to rural Minnesota lakes, with chloride concentrations in the urban lakes increasing at an annual rate of 1.8%. Other studies have demonstrated increasing chloride levels in streams and rivers (e.g. Kaushal et al., 2005; Kelly et al., 2012; Dailey et al., 2014; Corsi et al., 2015), the Great Lakes (Chapra et al., 2009, 2012), as well as in lakes of New Hampshire (Likens and Buso, 2010), Michigan (Koretsky et al., 2012; Sibert et al., 2015), Italy (Rogora et al., 2015), Canada (Environment Canada, 2001), and Sweden (Thunqvist, 2004) due to influx of road salt deicers. With continued use of road salt deicers, chloride concentrations in urban freshwater systems are likely to continue increasing.

Levels of chloride in many surface water systems now periodically or even permanently exceed the chronic toxicity threshold for freshwater species of 250 mg/L (e.g., Environment Canada, 2001; Kaushal et al., 2005; Mullaney et al., 2009; Corsi et al., 2015; Dugan et al., 2017). Increasing chloride levels can also affect the density structure, and thus potentially change the mixing dynamics, of freshwater lakes. For example, Judd (1970) found that wind action was insufficient to cause seasonal turnover of First Sister Lake in Michigan because of the increased salinity, and thus increased density of the lake bottom waters, created by the influx of road salts. Similarly, Novotny et al. (2008) observed that road salt contamination caused two urban lakes in Minnesota to transition from dimixis (twice per year mixing) to monomixis (once per year mixing), and Sibert et al. (2015) demonstrated that road salts caused an urban kettle lake in Michigan to transition to meromixis (no annual mixing). Both Novotny et al. (2008) and Sibert et al. (2015) reported hypolimnetic anoxia in these lakes, in part due to their failure to turnover.

Eutrophic lakes have high levels of nutrients and labile organic matter. In these lakes, the water column may become redox stratified as labile organic matter remaining after oxygen depletion is oxidized via a sequence of increasingly less energetically favorable terminal electron acceptors including nitrate, $Mn^{4+}$, $Fe^{3+}$ and $SO_4^{-2}$. This results in the production and accumulation of reduced solutes including $NH_4^+$,

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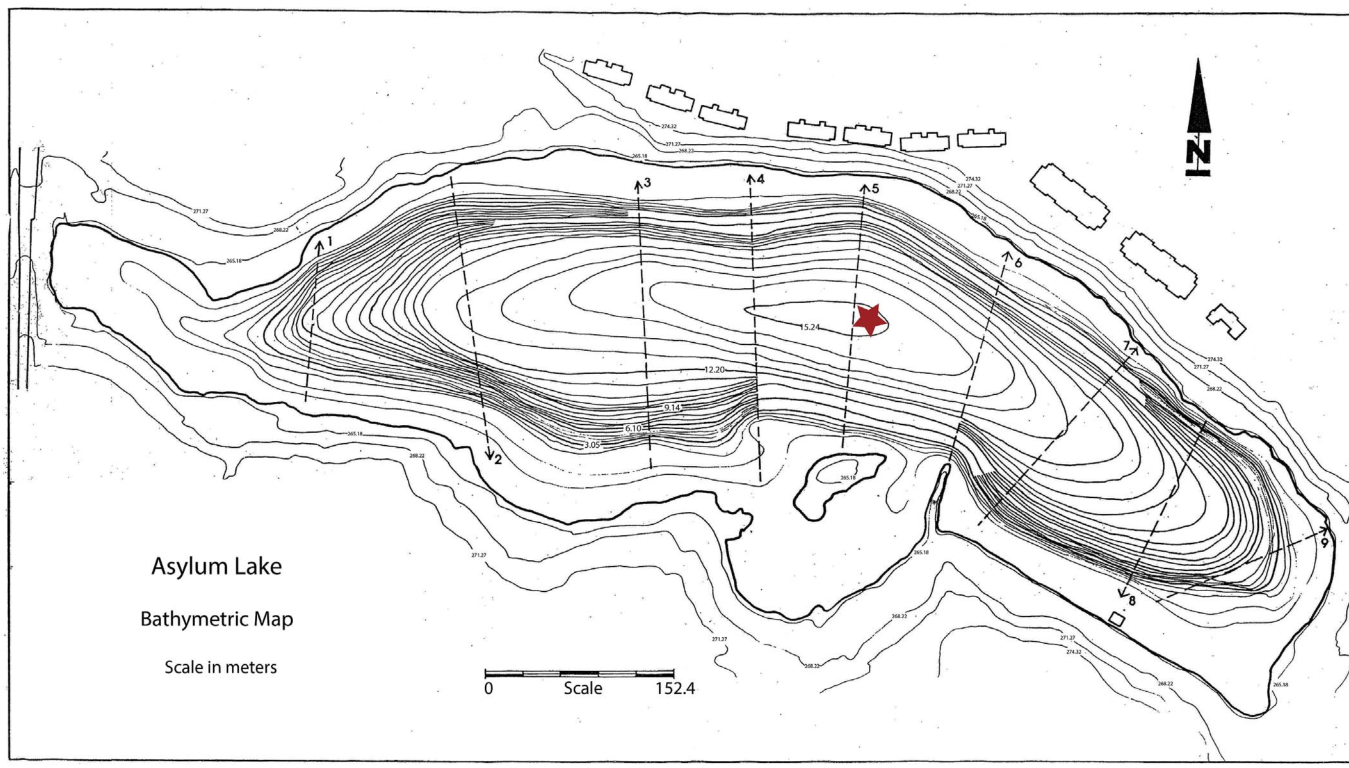


**Fig. 1.** Bathymetric map of Asylum Lake with sampling location noted by star. Map was created in 1991 by William Sauck (Institute for Water Sciences), William Laton (Department of Geology), and Bryan Allen (Department of Geology) using a Lowrance Model X-16 with 192 kHz transducer along numbered transects. Contour interval is 0.61 m.

$Mn^{2+}$, $Fe^{2+}$, $H_2S$ and $CH_4$ in the hypolimnion (Boehrer and Schultze, 2008; Koretsky et al., 2012; Sibert et al., 2015; Dupuis, 2017). If a eutrophic lake fails to turnover due to road salt contamination, hypolimnetic anoxia and redox-stratification may become permanent. Whether a lake transitions to meromixis due to road salt influx likely depends on the concentration of salt, the residence time of water in the lake, and the lake depth and surface area (Rodrigo et al., 2001).

In this study, the water column chemistry of a primarily groundwater-fed, eutrophic kettle lake located in urban Kalamazoo, MI was studied over a period of nineteen months to assess the influence of road salt contamination on seasonal turnover and the development of redox stratification in the lake.

## 2. Study site

Asylum Lake is an urban kettle lake located in Kalamazoo, MI, with a surface area of approximately 19.8 ha, a mean depth of 7.2 m, and a maximum depth of 15.8 m (Sauck and Barcelona, 1992; Kieser and Associates, 2008; Koretsky et al., 2012, Fig. 1). Water enters the lake primarily through groundwater discharge on the west side of the lake and exits the lake through groundwater recharge to the east, as well as via a small culvert leading to Little Asylum Lake. The residence time of water in the lake is estimated to be 0.68 years (Kieser and Associates, 2008). Asylum Lake is bordered by wetlands to the west, prairie and woods to the south, and by residential neighborhoods to the north. The soils around the lake are primarily Houghton and Sebewa soils characterized by excess humus and wetness (USDA, 1979). South of Asylum Lake, the soils are Kalamazoo loam with a 6–12% slope; north and west of Asylum Lake, the soils are Urban Oshtemo complex with slopes of 12–25%; southeast and southwest of Asylum Lake, soils are Oshtemo sandy loam with 18–35% slope and 12–18% slope, respectively (USDA, 1979). Kieser and Associates (2008) completed a topographic assessment of the surrounding watershed and concluded that it is comprised of ~34% forest or open herbaceous land; 30% farmland; 18% high/low density urban; 10% roads/parking lots; 4% wetlands; 3% water and 0.5% bare soil.

## 3. Materials and methods

Water column sampling was conducted at approximately the deepest point in Asylum Lake (Fig. 1) at 0.5 m intervals for *in situ* measurements of dissolved oxygen, pH, conductivity, and temperature and at 1 m intervals for *ex situ* samples. Water samples were collected approximately once a month from September 2012 to March 2014, with the exception of the period between mid-December 2012 and March 2013. During this time, ice thickness was such that it was unsafe to traverse the lake and no samples were collected. During periods of potential turnover, *in situ* samples were collected more frequently. Water samples were transported back to Western Michigan University and analyzed for $Fe^{2+}$, $Mn^{2+}$, orthophosphate, total $NH_4^+$, alkalinity, total sulfide ($\Sigma H_2S$), $Cl^-$, $SO_4^{2-}$, $Ca^{2+}$, $Mg^{2+}$, $K^+$, and $Na^+$ according to the methods described in Sibert et al. (2015).

## 4. Results

### 4.1. Temperature, dissolved oxygen, conductivity, and pH

Asylum Lake temperature profiles show strong thermal stratification in summer and early fall, weak stratification in late fall and early spring, and reverse stratification during all periods of ice cover. In December 2012, April 2013, November 2013, and April 2014 the lake is isothermal, indicative of potential turnover events (Fig. 2A).

The epilimnion is supersaturated with respect to dissolved oxygen in all seasons except during periods of ice cover (Fig. 2B). In the summer, the hypolimnion is hypoxic to anoxic below 6–9 m depth. In fall and spring, oxic conditions persist to depths of between 10 m and 13 m, except during isothermal conditions in late November 2013, when dissolved oxygen increases slightly with depth to 14 m and then decreases at 14.5 m (Fig. 2B).

In all seasons, specific conductivity in Asylum Lake increases with