Density Current Intrusions in an Ice-Covered Urban Lake

by

Christopher R. Ellis, Jerry Champlin,

and Heinz G. Stefan

Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Washington, D. C.

March 1997
Minneapolis, Minnesota
TABLE OF CONTENTS

Acknowledgement ...................................................................................................... ii
Abstract ....................................................................................................................... iii

1. Introduction ............................................................................................................. 1

2. Site Description ....................................................................................................... 2

3. Inflow and In-lake Salinity (Density) Measurements .............................................. 4
   3.1 Study Methods and Design .............................................................................. 4
   3.2 Results ............................................................................................................. 4

4. Temperature Measurements .................................................................................. 10
   4.1 Methods and Design ...................................................................................... 10
   4.2 Temperature Profile Dynamics in Time .......................................................... 10

5. Implications and Conclusions ................................................................................. 23

References .................................................................................................................. 25
ACKNOWLEDGMENT

The investigation described herein was conducted for the U.S. Environmental Protection Agency as part of a research program dealing with the alteration of water availability, water quality and fish habitat in cold regions by climate change. This particular investigation deals with lakes in spring. Barbara M. Levinson of the USEPA/ORD is the project officer. The EPA support is gratefully acknowledged.
Evidence is presented that snowmelt runoff from an urban watershed can produce density current intrusions (underflows) in a lake. Several episodes of density current intrusions are documented. Water temperatures and salinities measured near the bottom of a 10 m deep Minneapolis lake during the late winter warming periods in 1989, 1990, 1991, and 1995 show significant rapid changes which are correlated with observed higher air temperatures and snowmelt runoff. The snowmelt runoff entering this particular lake (Ryan Lake) has increased electrical conductivity, salinity, and density. The source of the salinity is the salt spread on urban streets in the winter. Heating of littoral waters in spring may also contribute to the occurrence of the sinking flows, but is clearly not the only cause.
1. INTRODUCTION

Urban runoff can carry significant pollution loads, including suspended sediments, nutrients and metals. The receiving water bodies are often streams and rivers of various sizes, and in some cities urban lakes and impoundments. In these latter cases, the impact of the polluted water input on water quality can be serious. Cities in Minnesota, for example, have long struggled with this problem. In this geographic location a significant portion of the annual urban runoff occurs in spring as snowmelt runoff.

In this paper we document for the first time an unexplored aspect of this snowmelt runoff—it's appearance as a density current at the bottom of urban lakes. This has importance in lake modeling for lake water quality management in general, since the density currents carry materials to the bottom of a lake where they may ultimately get buried in lake sediments if the lakes are deep and stratified, or from where they may become moved to the surface mixed layer if the lakes are shallow and easily mixed.

Density currents are submerged gravity driven flows which occur when inflows to a water body are denser than the ambient water. The inflow subsequently plunges and continues as a distinct flow which can be envisioned as a submerged stream. Density currents, also called underflows, are known to form intermittently on coastal continental shelves, in reservoirs and at effluent discharge sites. They have been observed and documented in all three of these environments. A review on density currents was recently given by Alavian et al. (1992). The mechanics of density currents have been described in various models, e.g. by Turner (1973), Akiyama et al. (1987) and many others. Density currents can also have an internal origin. For example, heating or cooling of littoral waters to maximum density or resuspension of sediment in littoral waters by waves can initiate density currents.

In a continuing investigation of temperature dynamics and transport processes in ice-covered lakes, the authors have collected evidence of the existence of density currents in urban lakes that result from snowmelt runoff. Presentation and analysis of this information is the focus of this paper. Heating of littoral water may have been a contributing factor.
2. SITE DESCRIPTION

Ryan Lake, located in Minneapolis, Minnesota, illustrated in Fig. 1, has been the site of this and previous research (Ellis and Stefan 1991). It has a surface area of 6.1 ha, a maximum depth of 10 m and a mean depth of 5 m. It is a highly eutrophic lake which occasionally experiences winterkill; the last occurrence of winterkill was in 1988. Ice thicknesses on the lake reach 0.5 m maximum. As the ice-cover develops, its open water volume decreases of 305,000 m$^3$ decreases by up to 10%. It receives inflow from urban storm sewers (I1 and I2 in Fig. 1), Intermittent Creek (I3), and direct road runoff (I4). During winter and spring snow melt, the majority of the inflow to the lake comes from one of the storm sewers (I1) and the intermittent creek from Twin Lakes (I3).
Figure 1  Bathymetry and surroundings of Ryan Lake, Minnesota. Surface water inflow points are labeled I1 to I4. Measurement locations are H, J, and K.
3. **INFLOW AND IN-LAKE SALINITY (DENSITY) MEASUREMENTS**

3.1 Study Methods and Design

Water temperature data were obtained with a Brooklyn precision mercury thermometer, which is accurate to within ± 0.05°C, and the conductivity measurements were taken with an American Marine Inc. PINPOINT conductivity monitor which has a stated accuracy of ± 5%. The correlation between conductivity and density was carried out under the assumption that NaCl is a close approximation (in terms of added density and ionic strength) to the salt applied to roads in Minneapolis. A Shimadzu Libror Model EB-4300DW scale was used to determine added density due to a range of salt concentrations. This procedure yielded the linear relationship (Champlin 1996)

\[
\text{Added Density} \ [kg/m^3] = 0.0004 \times \text{Conductivity} \ [mS/\text{cm}] \tag{1}
\]

3.2 Results

Evidence of elevated salinity in the inflows to the lake in spring is provided in measurements made in February and March, 1995. Temperatures, conductivities, and densities of the inflows to the lake are shown in Table 1. High salinity and density are evident. Maximum daytime air temperatures above 0°C and nighttime air temperature minima near 0°C usually cause snowmelt runoff events when the ground is snow-covered. When such air temperatures occur, runoff will follow within 0 to 2 days. The air temperature record shown in Fig. 2. provides an example of air temperature during a snowmelt period. Because the streets in the watershed are salted in winter, the first flush runoff carries this salt with it.

If snowmelt runoff causes density currents in the lake, salinities and densities at the bottom of the lake should reflect a change in salinity as time passes and density currents arrive. Table 2 gives measurements of salinity and density near the bottom of the lake at three different times in spring.

A detailed investigation of salinity in the vicinity of the storm sewer inflow 11 was conducted on March 13, 1995. It provided clear evidence of a plunging phenomenon very near the edge of the lake. Schematic drawings of this event are presented in Fig. 3, and data collected at the locations indicated in Fig. 3 are presented in Table 3.
Figure 3 shows schematics in both plan view and cutaway view of the density current observed on March 13, 1995 (Julian Day 72). The snowmelt water inflow cut through the ice surface near the culvert. The ice cover within 30 to 40 m of the shore near the culvert was under two to six inches of water. The majority of this overlying water is likely to be from snowmelt on the lake. This observation is supported by the surface conductivity measurements presented in Table 3. A density current is evident a few feet from the inflow into the lake: conductivity measurements at 0 and 0.3 m depths at locations A, C, and D indicate that the highly saline inflow plunges rapidly as it loses momentum entering the lake. The measurements at H justify the schematic shown in Figure 3 which is based on the model by Turner (1973).

The inflow temperatures reported in Table 1 in conjunction with the observed plunging phenomenon presented schematically in Figure 3 indicate that the probable source of the intrusions documented in the following section is the slightly saline snowmelt runoff. Heating of shallow littoral water through decaying ice and sediment in the surface runoff may have been contributing factors.
### TABLE 1. Inflow characteristics in spring

<table>
<thead>
<tr>
<th>Date</th>
<th>Air Temp. max, min[°C]</th>
<th>Location (Fig. 1)</th>
<th>Water Temp. [°C]</th>
<th>Conductivity [μSiemens]</th>
<th>Density [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/18/95</td>
<td>6.1, -3.3</td>
<td>I1</td>
<td>0.7</td>
<td>868</td>
<td>1000.264</td>
</tr>
<tr>
<td>3/13/95</td>
<td>14.4, 7.8</td>
<td>I1</td>
<td>4.5</td>
<td>1122</td>
<td>1000.444</td>
</tr>
<tr>
<td>3/13/95</td>
<td>14.4, 7.8</td>
<td>I3</td>
<td>0.7</td>
<td>622</td>
<td>1000.166</td>
</tr>
<tr>
<td>3/13/95</td>
<td>14.4, 7.8</td>
<td>I4</td>
<td>6.4</td>
<td>650</td>
<td>1000.152</td>
</tr>
<tr>
<td>3/17/95</td>
<td>15.5, 3.9</td>
<td>I1</td>
<td>5</td>
<td>220</td>
<td>1000.077</td>
</tr>
<tr>
<td>3/19/95</td>
<td>7.2, -1.1</td>
<td>I1</td>
<td>1.9</td>
<td>80</td>
<td>999.9981</td>
</tr>
<tr>
<td>3/19/95</td>
<td>7.2, -1.1</td>
<td>I3</td>
<td>4.3</td>
<td>565</td>
<td>1000.222</td>
</tr>
<tr>
<td>3/23/95</td>
<td>11.1, 1.1</td>
<td>I1</td>
<td>7.3</td>
<td>460</td>
<td>1000.097</td>
</tr>
<tr>
<td>3/23/95</td>
<td>11.1, 1.1</td>
<td>I3</td>
<td>8.3</td>
<td>490</td>
<td>1000.058</td>
</tr>
</tbody>
</table>
Figure 2  Air temperature record during the late winter 1994/95 (January 1 to March 31, 1995), including a snowmelt period from March 10 (Julian Day 69) to March 15 (Julian Day 74).
TABLE 2. Conductivities and densities of water near the bottom of Ryan Lake.

<table>
<thead>
<tr>
<th>Date</th>
<th>Air Temp. max, min [°C]</th>
<th>Location [Fig. 1]</th>
<th>Depth [m]</th>
<th>Water Temp.[°C]</th>
<th>Conductivity [μSiemens]</th>
<th>Density [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/18/95</td>
<td>6.1, -3.3</td>
<td>K</td>
<td>7.8</td>
<td>--</td>
<td>65</td>
<td>1000.023</td>
</tr>
<tr>
<td>2/18/95</td>
<td>6.1, -3.4</td>
<td>J</td>
<td>8.1</td>
<td>--</td>
<td>67</td>
<td>1000.024</td>
</tr>
<tr>
<td>2/18/95</td>
<td>6.1, -3.5</td>
<td>H</td>
<td>6.5</td>
<td>--</td>
<td>63</td>
<td>1000.025</td>
</tr>
<tr>
<td>2/24/95</td>
<td>2.8, -7.8</td>
<td>K</td>
<td>7.8</td>
<td>--</td>
<td>78</td>
<td>1000.028</td>
</tr>
<tr>
<td>2/24/95</td>
<td>2.8, -7.9</td>
<td>J</td>
<td>8</td>
<td>--</td>
<td>71</td>
<td>1000.025</td>
</tr>
<tr>
<td>2/24/95</td>
<td>2.8, -7.10</td>
<td>H</td>
<td>6</td>
<td>--</td>
<td>60</td>
<td>1000.021</td>
</tr>
<tr>
<td>3/12/95</td>
<td>15, 7.8</td>
<td>K</td>
<td>8</td>
<td>3.1</td>
<td>770</td>
<td>1000.369</td>
</tr>
<tr>
<td>3/12/95</td>
<td>15, 7.9</td>
<td>J</td>
<td>6.5</td>
<td>--</td>
<td>943</td>
<td>1000.305</td>
</tr>
</tbody>
</table>

TABLE 3. Temperature and conductivity measurements on March 13, 1995 to accompany figure 3.

<table>
<thead>
<tr>
<th>Location</th>
<th>Depth [m]</th>
<th>Water Temp. [°C]</th>
<th>Conductivity [μSiemens]</th>
<th>Density [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>0</td>
<td>4.5</td>
<td>1122</td>
<td>1000.4437</td>
</tr>
<tr>
<td>A</td>
<td>0</td>
<td>4.7</td>
<td>1000</td>
<td>1000.3928</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>1.5</td>
<td>232</td>
<td>1000.0451</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>1.5</td>
<td>242</td>
<td>1000.0491</td>
</tr>
<tr>
<td>D</td>
<td>0</td>
<td>1.5</td>
<td>236</td>
<td>1000.0467</td>
</tr>
<tr>
<td>E</td>
<td>0</td>
<td>1.2</td>
<td>208</td>
<td>1000.0355</td>
</tr>
<tr>
<td>F</td>
<td>0</td>
<td>1.3</td>
<td>200</td>
<td>1000.0204</td>
</tr>
<tr>
<td>G</td>
<td>0</td>
<td>1.2</td>
<td>200</td>
<td>1000.0245</td>
</tr>
<tr>
<td>H</td>
<td>0</td>
<td>--</td>
<td>150</td>
<td>1000.0003</td>
</tr>
<tr>
<td>B</td>
<td>0.3</td>
<td>--</td>
<td>1000</td>
<td>1000.3973</td>
</tr>
<tr>
<td>C</td>
<td>0.3</td>
<td>--</td>
<td>840</td>
<td>1000.3334</td>
</tr>
<tr>
<td>D</td>
<td>0.3</td>
<td>--</td>
<td>800</td>
<td>1000.3174</td>
</tr>
<tr>
<td>H</td>
<td>0.3</td>
<td>612</td>
<td>1000.2358</td>
<td></td>
</tr>
</tbody>
</table>
Figure 3  Schematic of density current intrusion. Differences of shading indicate variable water density.
4. TEMPERATURE MEASUREMENTS

4.1. Methods and Design

On February 1, 1991, an array of 20 thermistor-type temperature probes attached to a 5 m long rigid pole was positioned in and above the sediment of Ryan Lake at its deepest point such that 2 m of the pole was buried in the sediment and 3 m extended above it. Enough flotation was added to the pole to make it neutrally buoyant and prevent it from sinking further into the sediment after its initial placement. With the pole properly positioned, one probe was located at the sediment surface, 8 probes were located below it, and 11 probes were located above it. Both in the sediment and water, probes were placed closer together near the sediment/water interface where the greatest gradients in temperature were anticipated. The error associated with probe placement was ± 1.0 cm (absolute).

The thermistor probes were attached to 2 Campbell Scientific CR10 dataloggers which were programmed to make temperature measurements every minute. Every 20 minutes, the last 20 measurements were averaged and stored for later retrieval. To capture perturbations in the temperature structure, all of the 1 minute measurements made in the water column and at the sediment surface were stored if any measured water temperature differed by more than 0.1°C from the probe's previous measurement until either the data were retrieved or 24 hours had elapsed, whichever happened first. This measurement scheme provided both data with relatively low resolution in time (20 minute averaged data) during periods exhibiting relatively steady temperatures and higher temporal resolution during more dynamic periods (i.e., during the occurrence of transients). Such a scheme was necessitated by memory limitations of the dataloggers. Errors associated with differential measurements (successive measurements made by the same probe) were ± 0.1°C while absolute accuracy of the calibrated probes was ± 0.5°C.

4.2. Temperature Profile Dynamics in Time

A measurement record of the 1 minute data of 3 probes in the water column is shown in Fig. 4. The quasi-steady water and sediment temperatures prior to February 4 and the perturbation events that occurred thereafter are noteworthy. No appreciable thaw had occurred between early December and February 4, at which time roughly 20 cm of snow cover was lost in a three-day period (Fig. 5). The first perturbation appeared in the water temperatures after 2000 hours on 3 February and was restricted to the bottom 2 m of the water column (Fig. 6). The record is typical of the "head" of a density current (underflow) which begins as a very thin layer at the sediment surface and progressively thickens to 2 m, 5 hours
later. A much larger perturbation was recorded commencing at 1400 hours on 4 February. This event affected all monitored portions of the water column (0 to 3 m above the sediments) almost immediately and dropped overall water temperatures in that layer by about 1°C. Temperature fluctuations associated with the arrival of the intrusion damped out somewhat in the following 23 hours when a smaller secondary perturbation appeared at 1300 hours on February 5.

That temperature transients show the presence of density underflows is supported by the fact that the bulk of the previously deposited snow cover melted on February 3 and 4. A substantial inflow to the lake from the storm water culvert on the east shore was observed on February 3. Without dissolved or suspended contaminants, this water of unknown but probably near-freezing temperature would not be expected to plunge as a density current to the lake bottom since 0°C water is usually the lightest water under ice. However, since salt had been applied to the streets in the watershed for the previous two months and there had been no significant thaw to remove it, the inflow was saline causing it to be more dense, even the 4°C water near the lake bottom.

The interpretation of the temperature record as a density current intrusion facilitated by a plot of isotherms over depth and time (Fig. 6). Isotherms from 2.9°C - 4.4°C are plotted covering a height of 3 m above the sediment/water interface from February 2 to February 9. If the time (horizontal) scale is interpreted as distance seen by a traveling observer or recorder, Fig. 6 can be interpreted as a representation of the head of a density current moving from right to left. Its shape more clearly shown in a report by Ellis et al. (1997) is similar to that reported in the literature (Ippen, 1966; Harleman, 1960). Wave-like disturbances are readily apparent in the shear layer where temperature gradients are the strongest.

A number of other perturbations/intrusions appear in the temperature record later in February and in early March 1991. Again, these episodes occurred at times when air temperatures were above freezing and snow cover was melting.

Intrusions of density currents resulting from snowmelt were observed also in the late winters of 1989 and 1990 in which similar water temperature measurements were made. Three events are illustrated in Figs. 7 to 12 along with their associated air temperature records.

Air temperature records before, during and after the density current intrusion observed in 1989 are given in Fig. 7. Air temperatures were rising during the two days preceding the density current observation from -10°C to +7°C during the day. These temperatures are sufficient to produce snowmelt runoff from city streets. Lake water temperatures had been monitored using a thermistor chain since 8 February from the surface to the 8 m depth. Isotherms interpolated from the data are shown in Fig. 8. The arrival of the density current on March 10 (Julian day 69) is evidenced by a sudden water temperature drop from 3°C to 2.4°C at the 8m depth. Propagation of the disturbance associated with the arrival of the density current can be seen to extend all the way to the ice cover.
The sudden appearance of 2.4°C water near the lake bottom underneath 2.8°C water can only be explained as an impurity laden (saline) density intrusion.

Two similar events were observed in 1990, the first on 21-22 February (Julian day 52-53 in Fig. 10) and the second on 7 March (Julian day 66 in Fig. 12). Again, both events corresponded with thawing (above freezing) conditions of the ambient air (Figs. 9 and 11). On 21 February, the sudden appearance of 3.3°C water near the lake bottom where hours earlier quiescent, stably stratified 4°C to 4.2°C water had existed, points to the intrusion of an impurity-laden cold underflow originating from snow-melt runoff. Likewise on 7 March, a near-bottom disturbance can be seen which lags by about 24 hours behind the onset of above freezing air temperatures. It may be noted that the uncharacteristically high water temperatures in the upper part of the water column and the near complete lack of stratification during the week of 5-11 March (Fig. 12) were due to solar heating of the water column through a snow-free ice cover.
Figure 4  One minute water temperature data recorded at selected depths above the lake bottom, 3-6 February 1991. Major cold water intrusion on 3 and 4 February.
Figure 5  Records of air temperatures, snowfall and cumulative snow depths during winter 1990/91 (1 December 1990 - 31 March 1991).
Figure 6a  Isotherms of 1 minutes water temperature measurements, illustrating on the left the front of a cold water intrusion beginning on 3 February (Julian Day 34) 1991, followed on the right by a second intrusion on 4 February (Julian Day 35).
Figure 6b  Isotherms in the bottommost 3m of water in Ryan Lake from 2 February to 9 February 1991. Stable stratification on the first two days is disturbed on the following two days. Water is again stratified at the end of the period, but colder.
Figure 7  Record of air temperatures during the late winter 1988/89 and at the time of the observed cold water intrusion in Ryan Lake, 10 March 1989.
Isotherms in the upper 8m of water in Ryan Lake from 7 March to 13 March 1989. Disturbance of stable stratification by cold water intrusion on 10 March (Julian Day 69). Stratification at end of period shows lower temperature near bottom and thinner thermocline layer below the ice, presumably due to mixing induced by cold water intrusion.
Figure 9 Record of air temperatures during the late winter 1989/90 and at the time of the cold water intrusion recorded in Ryan Lake on 21 and 22 February 1990.
Figure 10  Isotherms in the deepest water column of Ryan Lake from 18 February (Julian Day 49) to 24 February (Julian Day 55) 1990. Disturbance of the stable stratification by a cold water intrusion on the bottom of the lake on 21 February (Julian Day 52).
Figure 11  Record of air temperatures at the time of the cold water intrusion recorded in Ryan Lake on 7 March 1990.
Figure 12: Isotherms in the deepest water column of Ryan Lake from 5 March (Julian Day 64) to 11 March (Julian Day 70) 1990. Disturbance of the stable stratification by an intrusion on the bottom of the lake on 7 March (Julian Day 66).
5. IMPLICATIONS AND CONCLUSIONS

Substantial evidence has been presented that early spring warming in a cold region urban watershed brings density current intrusion in lakes. These currents have been linked to snowmelt runoff and increased salinity in the runoff water. The study reported herein was conducted in an urban area where roadsalt is regularly applied.

The lag time between above freezing air temperatures and the appearance of density current intrusions has been observed to be 0 to 2 days. Thicknesses of these currents have been observed to be on the order of several meters. After their passage, the entire lake stratification is disturbed and bottom temperatures are often cooler.

The four episodes of urban snowmelt runoff density current intrusions in a Minneapolis lake reported, occurred between February 4 and March 10. A typical ice-out date for the lake is April 1. Spring overturn (4°C uniform lake temperature) occurs shortly thereafter.

Snowmelt runoff from urban watersheds into lake therefore precedes spring overturn by several weeks. The reason is that a much larger portion of the incoming solar radiation in spring is captured by the street surfaces, roofs, and building surfaces, than by the snow and ice-covered lake surfaces. Often streets and buildings are free of snow and ice, while urban lakes still have a complete ice cover. The physical reason is the difference in the albedo of street and building surfaces (0.05 to 0.20) and snow (0.7 to 0.9) and ice (0.3 to 0.80).

It was shown herein that urban snowmelt runoff flows to the deepest portion of a lake. Because of the timing of snowmelt runoff, it will still be at the lake bottom when the lake turns over in spring. Being slightly more saline, the layer of snowmelt runoff water has the potential to prevent the complete overturn (mixing) of the lake to its very bottom. Instead, the slightly saline snowmelt water layer may cause at least a temporary mesomixis.

There is at least one lake (Brownie Lake) in the Minneapolis chain of lakes with documented mesomixis due to street salt runoff. Brownie Lake has a year-round saline bottom layer and is a very small and relatively deep lake set in a deep topographic depression. It is a very wind-sheltered lake. The half-life of the snowmelt runoff layer in Ryan Lake is not known at this time. In this study, we have documented previously uncaptured events which indicate the formation of the layer. Its ultimate fate will be explored through further field studies and modeling of the vertical mixing near the bottom of lakes after spring (snowmelt runoff).
The study reported herein has also established that in one-dimensional models of urban lake water quality, urban snowmelt runoff water volume and its solids content can be placed into the bottom-most layer. The likelihood that suspended materials, which snowmelt runoff imports to an urban lake, settle out and are buried in lake sediments is therefore very high. The distribution of dissolved materials, e.g. nutrients from the snowmelt runoff in the lake, will depend whether the receiving lake bottom layer resists vertical mixing or not, which can be determined based on the vertical salinity (density) gradients, lake size and depth and weather (wind) conditions.

One implication of this observation then is that in early spring (February and March) while urban lakes are still mostly ice-covered, urban watershed runoff carries materials accumulated on city streets quickly and efficiently to the bottom of lakes. In addition to potassium and calcium chlorides, these materials may include nutrients and metals. The concentrations are apparently small and no mesomixis during the remainder of the year has been reported.
REFERENCES


