Walking on Water:
A Study of Winter Lake Mixing in Upper Lyman Lake

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INTRODUCTION

Our study explores lake mixing in Upper Lyman Lake, a small, man-made body of water on Carleton College's campus in Northfield, Minnesota. Lake mixing has been studied around the world using a variety of methods. Most studies begin with the construction and analysis of a temperature profile of the lake of interest (Bengtsson, 1986, 1996, Stevens, 2004, Rimmer, 2005). A temperature profile indicates where and how the lake water circulates. For example, heat sources such as sediments, groundwater, through-flow, and solar-radiation can cause convective currents (Bengtsson, 1996, Lorke, 2003). The presence or absence of distinct thermal layers also reflects the degree of lake mixing. Information obtained from temperature studies are frequently refined using tracer tests. Common tracer tests employ fluorescing dyes (Otz 2003, Stevens 2004) or natural tracers such as the chloride ion (Rimmer 2005). While lake mixing research is prolific, few comprehensive studies have been done on ice-covered lakes. Lars Bengtsson's studies of ice-covered lakes are thus most relevant to our research (Bengtsson 1986, 1996).

Our findings about Upper Lyman Lake fall into two main categories: temperature and water flow. We discovered two main temperature trends. First, the temperature of the water increases with depth and this gradient is sharpest in the top 150 cm of the lake. Second, the temperature variation over time is more pronounced in the upper level of the lake than in its depths. Building upon this understanding of temperature distribution in the lake, we investigated water flow, determining that in addition to Spring Creek, groundwater springs are likely a significant source of water inflow.

First, we will present our temperature data and discuss both probable causes for the temperature gradient and its implications for lake-mixing. Next we will discuss both the impact of through-flow from Spring Creek and the likely effects of inflow from groundwater springs.

We will conclude with suggestions for further study.

PREVIOUS WORK

History of Lyman Lakes

Lyman Lakes were created in 1916 and 1917 by digging out lakebeds and damming Spring Creek ("Lyman Lakes…"). To clear the excess sediment that Spring Creek continued to deposit in the lake beds, both Upper and Lower Lyman were re-dredged in the winter of 2000, and a system was installed to control the influx of sediments (Miller par. 1). This dredging dramatically increased the volume of Upper Lyman basin from 300,560 cubic feet to 705,564 cubic feet (Easley), and resulted in a new depth of 10 feet (Figure 1).

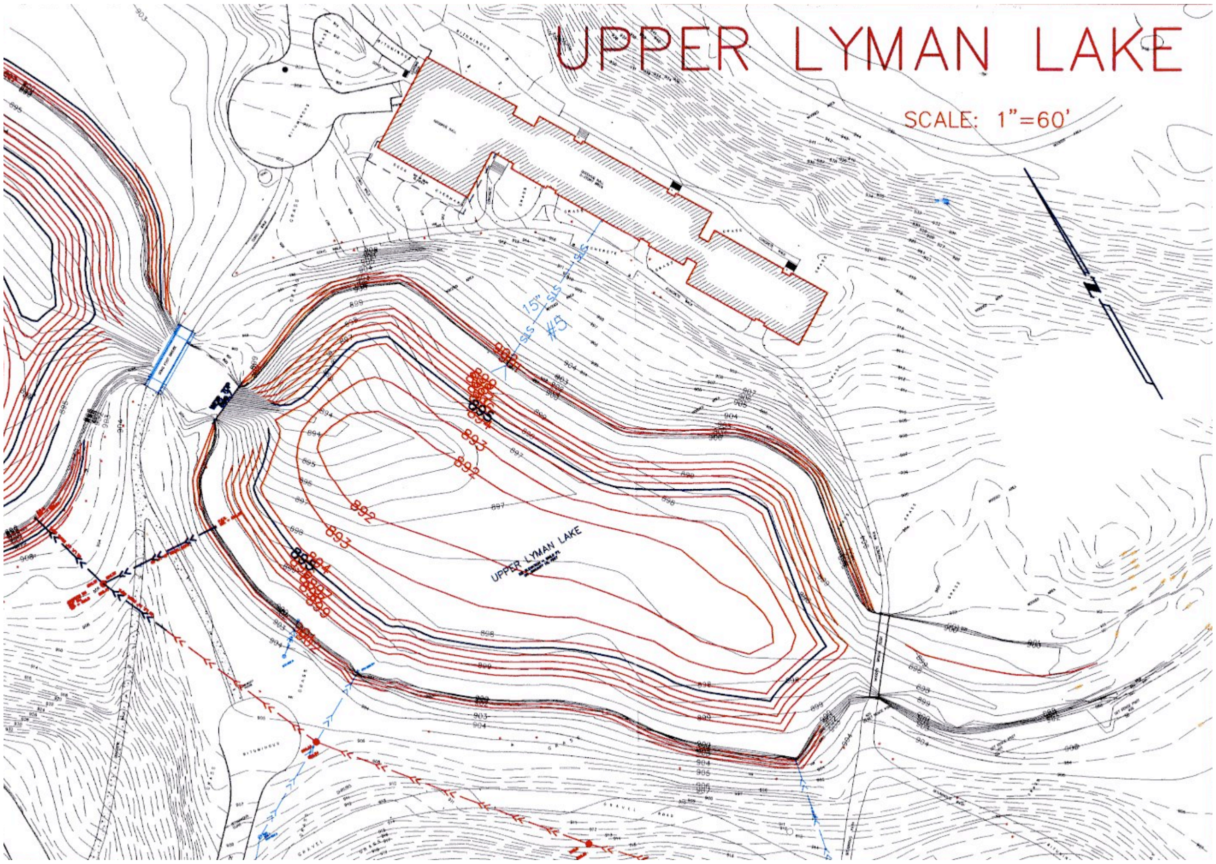

Figure 1. Topography of Upper Lyman Lake after dredging (in red) in 2000

Previous studies of Lyman Lakes

Two studies of Upper Lyman Lake have recently been conducted by Carleton Geology students: “Water Chemistry of Upper Lyman Lake” (2003), and “A Study of the Lyman Lakes and Spring Creek” (2004). The 2004 study, like ours, included measurements of temperature, conductivity, and flow rate. Because of its broader geographic focus, however, it included just four shoreline sample points in Upper Lyman Lake. By studying the large-scale temperature, conductivity, and flow patterns of Upper Lyman Lake during a period of ice cover, we depart from these previous works considerably.

Previous studies of lake mixing

Extensive studies of lake mixing have been conducted in the past, varying widely in geographic location, lake size, and technique. The vast majority of these studies, however, have been done on lakes without frozen surfaces. The difference is crucial, because the wind-induced mixing and the heat exchange between the air and the water that most scientists focus on become largely inapplicable when a lake is covered in ice. The most prominent studies of mixing in ice-covered lakes were conducted by Lars Bengtsson in the mid-nineties. After conducting experiments on Lake Pratstholm, Lake Malaren, Lake Erken, and several other small Swedish and Norwegian lakes, Bengtsson concluded that currents ice-covered lakes are primarily generated “by river through-flow and by heat flow from the bottom sediments on shallow water causing slow bottom currents toward deeper water.” Wind-induced oscillation of the ice cover will also indirectly induce horizontal mixing, while solar radiation can potentially induce convective mixing depending upon the transparency of the ice cover (Bengtsson,1996).

Most lake-mixing studies that have been conducted (of both ice-covered and ice-free lakes) begin with a thorough analysis of the temperature distribution throughout the lake in question. Despite the conclusion that isolation from the atmosphere results in minimal temperature change within an ice-covered lake, Bengtsson also remarks that “in small lakes very sharp temperature gradients may develop close to the ice” (Bengtsson, 1996). Lorke and Wuest also emphasize that the water directly below the ice-covering will be cooler than denser water toward the bottom of the lake, and that the warming effect of solar radiation depends upon the amount of snow on the ice cover. The thickness of the relatively stable, cold, less-dense top layer—probably a few tens of centimeters—depends upon the background salinity and the melting rate of the ice (Lorke and Wuest, 2003).

Almost all of the previous studies that we encountered also used some form of tracer to track lake mixing. For example, the Kootenay study injected a fluorescing dye, Rhodamine WT, into the lake using a hose, and then tracked and graphed dye concentrations as a way to trace water movements. In a different study, conducted in Switzerland, tracers were used to track interactions between lake water and groundwater. (Otz., et. al., 2003). Naturally occurring chemicals such as chloride ions can also serve as tracers, as the Lake Kinneret and Lake Biwa studies demonstrate. Although we did not perform tracing tests, they are a promising tool for future study.

METHODS

Measuring water temperature

Our first step was to try to create a temperature model of the lake. We measured the water temperature of Lyman Lakes on five separate days between Tuesday, January 31 and Thursday, February 23 of 2006. For this, we used two devices: the YSI 85 and the YSI 33, both of which are oxygen, conductivity, salinity and temperature meters. All temperatures were measured in degrees Celsius.

Because the surface of the lake was almost entirely frozen while we were doing our study, we needed to make holes in the ice in order to get the temperature probes in the water. We made these using a simple ice pick, then later an auger. The holes were about 6 to 8 inches in diameter.

Except on the first day, when we were working at shallow depths around the edges of the lake, we measured temperature by taping the probe to a long, retractable plastic measuring pole and lowering it into the hole in the ice. This helped us create an accurate vertical temperature index at each spot and to measure depth in the middle of the lake. We measured temperature at 20 cm increments, sometimes 50 cm.

In choosing our test points, we divided the lake into five cross sections (Figure 2). Since Andrew was cutting most of the holes, we measured the horizontal distance between the holes in "Andrew paces"—22 between each hole on the three north/south cross sections and 25 between each hole on the single east/west axis. We made additional holes at points near the inlet and outlet, beyond the bridge, and along the north bank. For our East-West and shoreline test points, we were able to return the following week and re-measure by re-breaking the scar we had left on the surface of the ice.

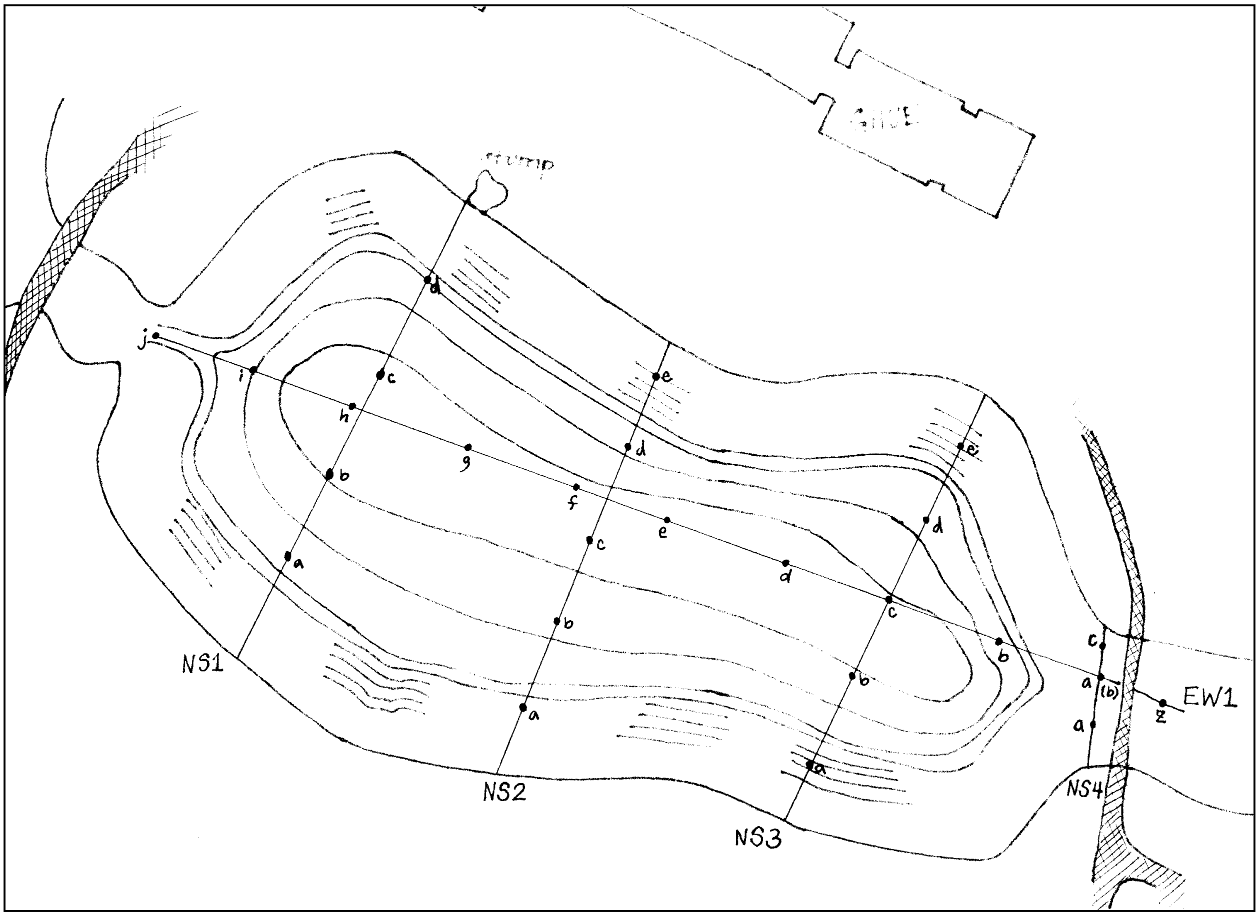

Figure 2. Upper Lyman Lake Testing Points

Measuring ground water temperature

When we tried to measure ground water temperature on Thursday, February 24, we used a point on the southern shore of the lake. We made a hole into the ice, then pounded a metal pipe with a conical perforated attachment, through about 6 feet (1.82 meters) of bottom sediment. We then sent the temperature probe down through the pipe and measured the temperature of the groundwater that came through the perforations in the pipe. To get an accurate measurement, we had to wait for equilibrium to establish between the groundwater and the inside of the pipe.

Measuring conductivity

At many of the points where we recorded temperature, we occasionally took water samples in sterile plastic containers. We later analyzed the conductivity levels of these samples in the laboratory using the YSI 85 meter. Other times, we simply read the conductivity reading from the YSI probe while we were collecting temperature data in the field. All conductivity measurements were recorded and expressed in µs or ms.

Measuring the velocity of water flow

On Tuesday, February 14, we measured the rate of water flow underneath the ice using a Flo-Mate water velocity meter. We attached the probe for the Flo-Mate to the same kind of measuring pole we used with the temperature probe. Because the probe on the flow meter has to be pointing in the direction of the flow to give an accurate reading, we assumed that the water would flow directly from the inlet to the outlet. We clamped the probe securely to the pole and made sure that the side it was on always faced the bridge over the inlet. We made most of our measurements along the EW1 axis and near the inlet and outlet. Flow measurements were recorded in meters per second (m/s).

RESULTS

Figure 3. Temperature vs. Depth by Date

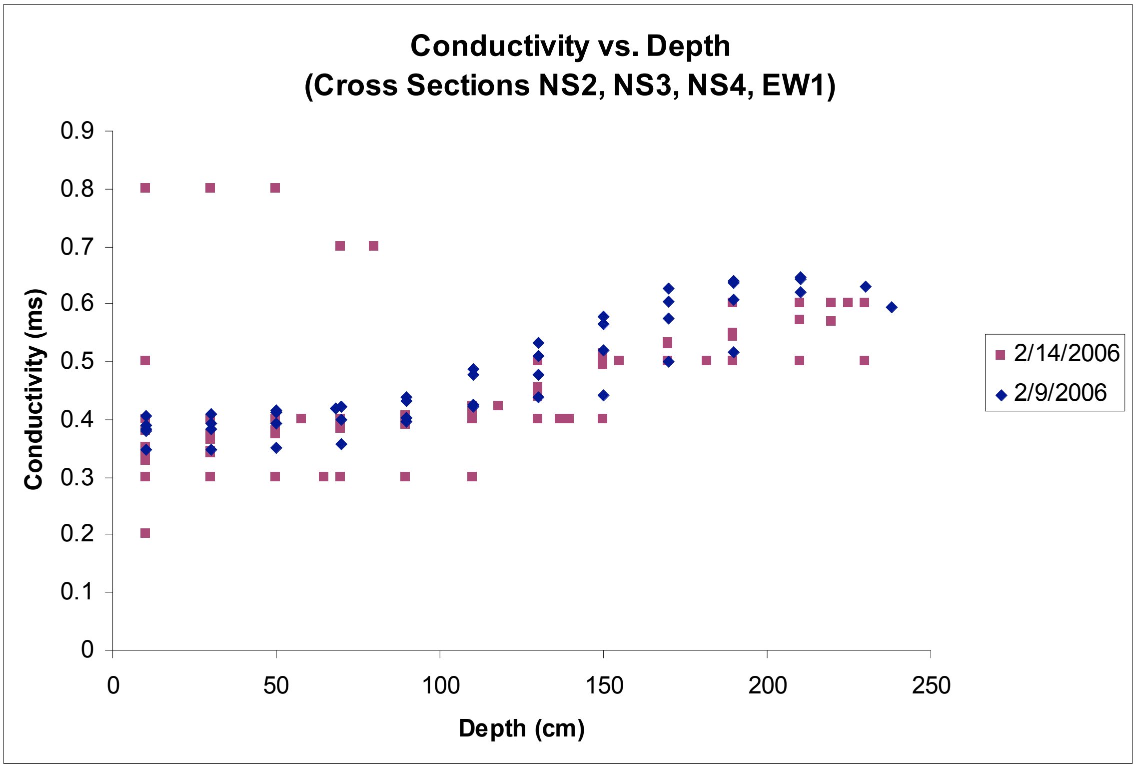

Figure 4. Conductivity vs. Depth

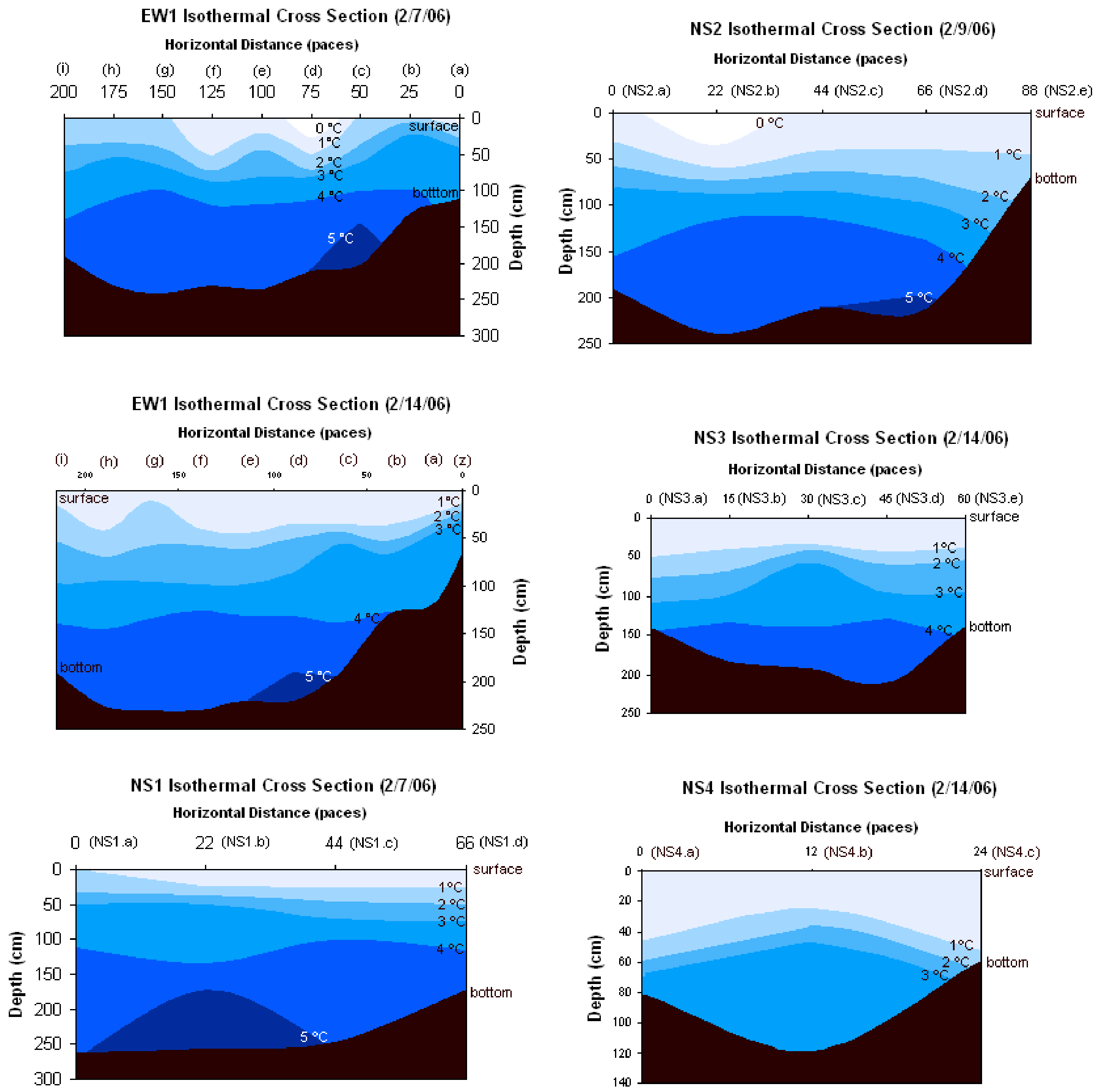

Figure 5. Isothermal Cross Sections obtained by interpolation and extrapolation of temperature and depth data (see Appendix A for full results). The 5 °C isothermal lines are particularly uncertain.