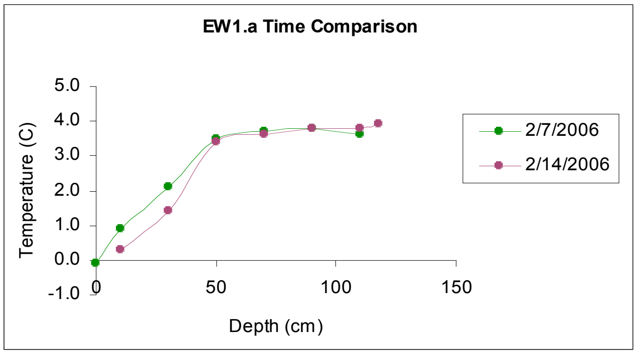

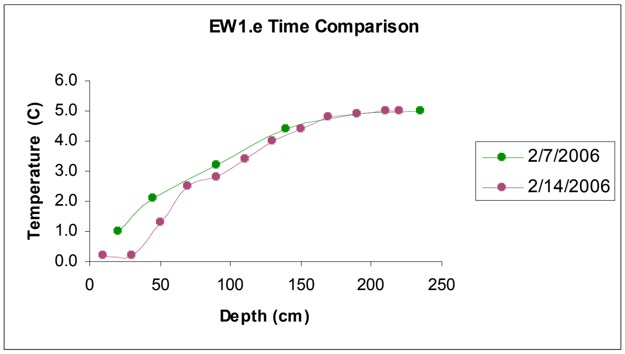

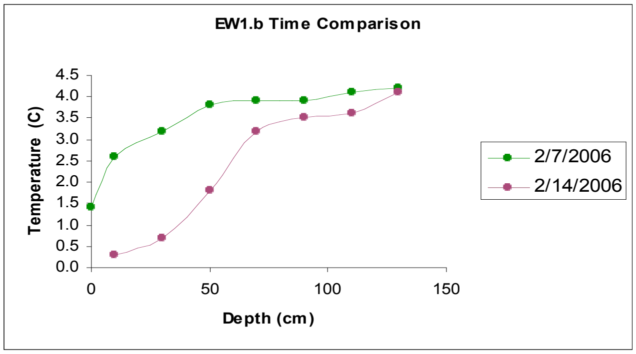

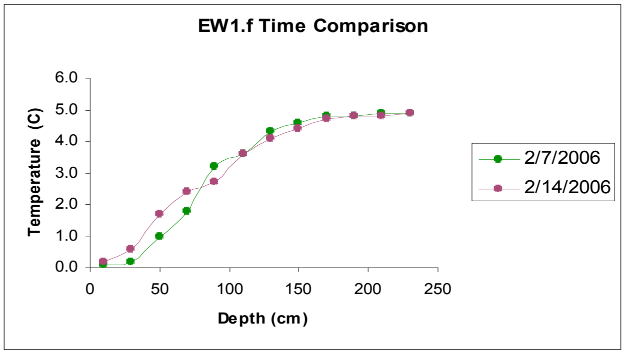

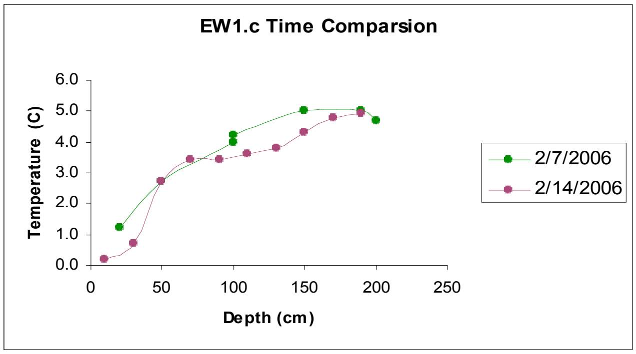

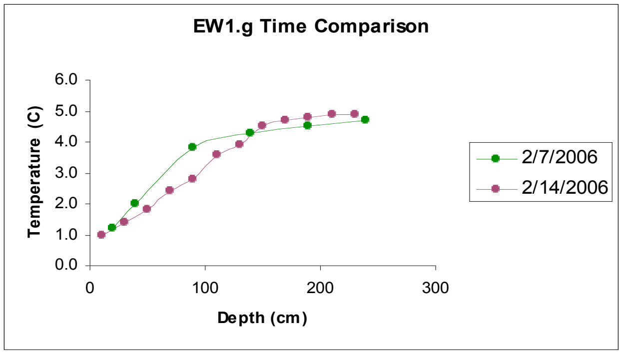

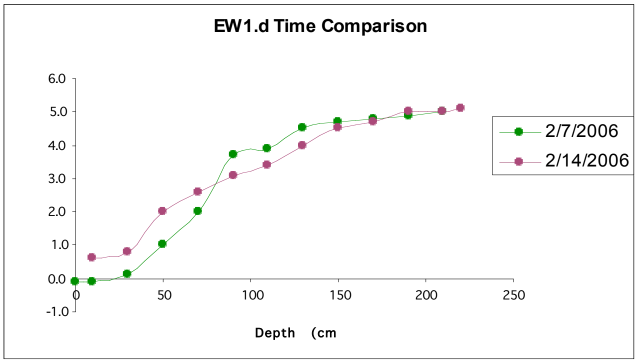

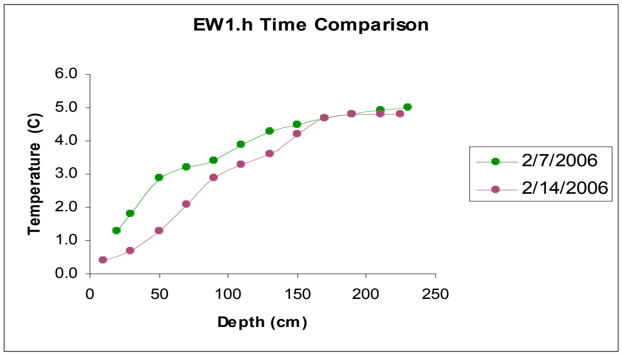

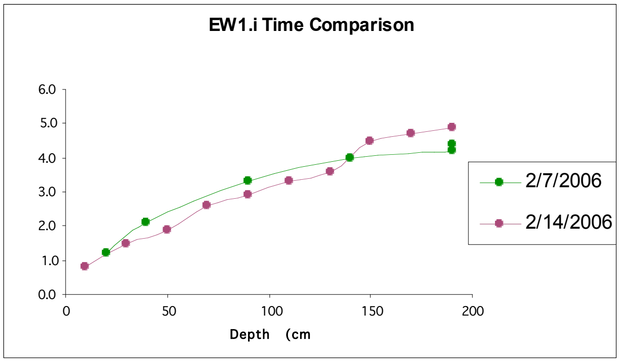

Figure 7. Temperature Profiles
These graphs compare temperature profiles at nine points along the east-west cross section of Lyman Lakes for two separate measurement dates, spaced a week apart.

	Location	Distance from Inlet (paces)	Average Water Temperature (°C)
7-Feb	EW1.a	0	2.5
	EW1.b	25	3.4
	EW1.c	50	3.8
	EW1.d	75	2.9
	EW1.e	100	3.4
	EW1.f	125	3.2
	EW1.g	150	3.4
	EW1.h	175	3.7
	EW1.i	200	3.2
14-Feb	EW1.z	-25	2.7
	EW1.a	0	2.9
	EW1.b	25	2.5
	EW1.c	50	3.2
	EW1.d	75	3.4
	EW1.e	100	3.2
	EW1.f	125	3.2
	EW1.g	150	3.4
	EW1.h	175	3.1
	EW1.i	200	3.1
	EW1.j	225	3.0

Table 2. Average Temperatures as Distance from Inlet Increases

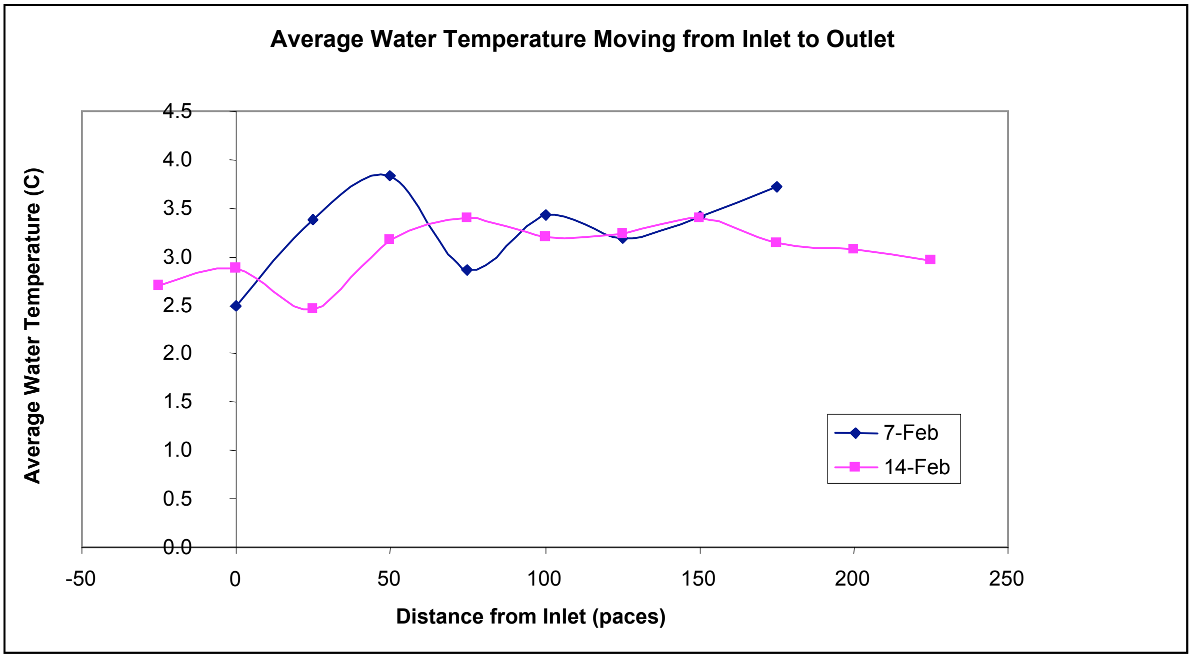

Figure 8. Average Water Temperature Moving from Inlet to Outlet

Temperature (°C)	**Depth below lake bottom (m)**	**Location**
3.2	1.8	~1m from lake's west edge

Table 3. Ground Water Temperature (2/23/06)

	Flow Rate (m/s)							
Depth (cm**)**	EW1.a	EW1.b	EW1.c	EW1.d	EW1.f	EW1.h	EW1.i	EW1.j
10	0.01	0	0	0.01	0	0	0.01	
25	0.01	0.01			0.01	0		
50	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
75	0.02	0.02			0.01	0.01		
80	0.01							
100		0.01	0.01	0.01	0	0.01	0.005	0.01
125					0.005	0.01		
150			0.01	0	0.005	0.005	0.005	0
175						0.01		
180			0.01					
200				0.01		0		
220						0		

Table 4. Flow Rate Measurements (2/14/06)

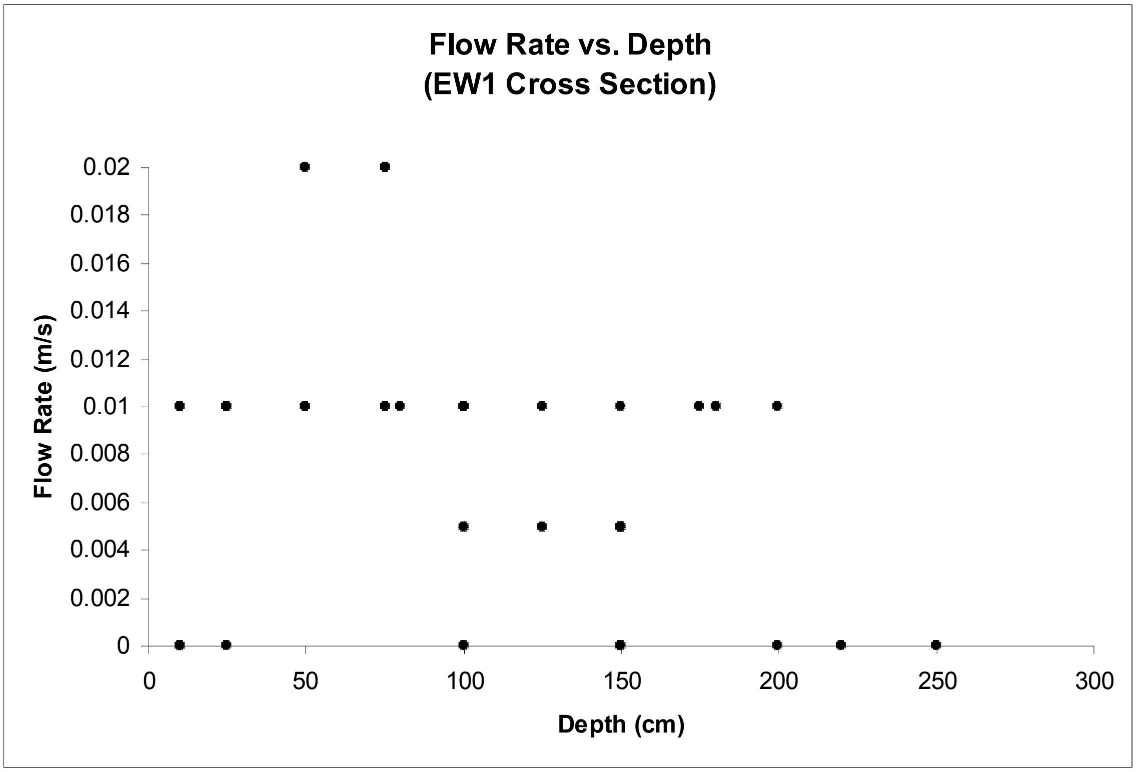

Figure 9. Flow Rate vs. Depth (2/14/06)

DISCUSSION

The two most pronounced temperature trends in Upper Lyman Lake—the overall increase in temperature with depth and the sharper temperature gradiant near the surface—are both well-illustrated in Figure 3. First note the overall increase in temperature from around 0°C at the surface to around 5°C in the deepest parts of the lake. Because the temperature is not uniform, it is clear that complete vertical mixing does not occur. While the temperature increases rapidly between 0 and 150 cm below the surface, the increase from 150 to 250 cm is more gradual. These same trends are apparent in the isothermal cross sections (Figure 5.), where the close spacing of isothermal lines near the lake's surface reflect the steep temperature gradient just below the ice. According to Bengtsson, this is a common trend in small, ice-covered lakes (Bengtsson, 1996).

Variations in the density of water due to both temperature and salinity help to explain the temperature gradient that we found. As Figure 10 demonstrates, water actually increases in density as it is warmed from 0°C to about 4°C. It therefore makes sense that the colder, less dense water is found near the surface and the warmer, denser water near the bottom.

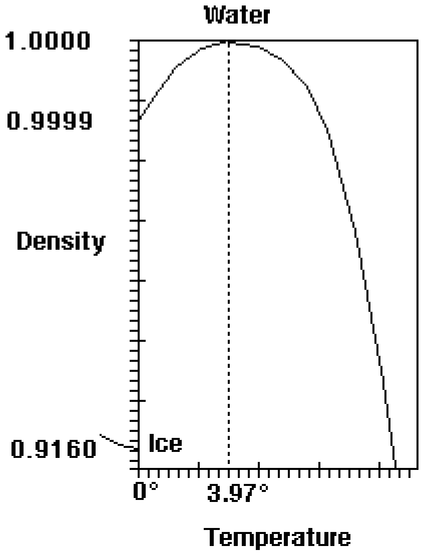

Figure 10. Water Density vs. Temperature
Source: http://tidepool.st.usm.edu/Crswr/ice.html

The water at the bottom of the lake above 4°C appears anomalous, however, until salinity is taken into account. As Bengtsson notes, "[s]alts frozen out during ice formation can be found near the bottom and make it possible for bottom water to be warmer than 4°C" (Bengtsson, 1996, p. 97). Because solutes increase the density of water, high-salinity 5°C water could actually be denser than lower-salinity 4°C water. It would therefore not rise as we might expect if we considered only temperature. Figure 4 shows that the conductivity (an indication of salinity) of water in Upper Lyman does indeed increase with depth, which supports this explanation.

In addition to density, heat transfer mechanisms may contribute to the coldness near the surface and warmth near the bottom. Because Upper Lyman Lake was consistently covered in snow, solar radiation probably had a minimal warming effect. Instead, some combination of ice melting (Lorke, 2003) and heat transfer to the ice from sub-surface waters (Bengtsson, 1996, pp. 91-92) probably contributed to the cold temperatures just below the ice in Upper Lyman. Two sources of heat may warm the lake waters from the bottom. First, sediments transfer heat to lake water during the winter (Bengtsson, 1996, p. 91, Lakes: Chemistry, Geology, Physics 1978). Second, warmer groundwater may be feeding the lake through springs. We will discuss the possibility of these springs shortly. Heat transfer is an important consideration for lake mixing because it can give rise to convective currents. The extent to which sediments and groundwater springs give rise to convective currents is probably limited at present by the density structure of the lake. However, our information is insufficient to draw firm conclusions.

To track temperature variations in Upper Lyman over time, we measured temperature at incremental depths along the EW1 cross section on two different occasions, spaced a week apart. We then graphed the temporally separate temperature profiles together for each testing site (Figure 7). Most sites follow a general trend: on 2/14/06, the upper levels of the lake were cooler, but the temperatures for the two days converge at depth. Ice melting caused by a 2.0°C high air temperature (Table 1) may have cooled the near-surface waters on 2/14. However, this cooling effect did not seem to reach the depths of the lake. Because, as noted above, the ice melt is the least dense of lake water, perhaps it naturally remained buoyant, preventing mixing with the warmer waters below and minimizing its cooling impact. The relationship between long-term air temperature trends and lake water temperature is less certain. As Figure 7 shows, the week preceeding 2/7 was much warmer on average than the week preceeding 2/14. It therefore seems reasonable that the lake water was warmer overall on 2/7.

Having gained a fairly comprehensive understanding of the temperature distribution in Upper Lyman, its probable causes, and its significance for vertical mixing, we turned our attention to the flow of water through the lake. The most obvious source of this water is Spring Creek, which was originally dammed to create the lake and now flows through it. Our measurements of flow rate along the major East-West axis of the lake yielded fairly uniform readings ranging from 0.00 to 0.02 m/s, with no clear relationship between flow rate and depth (Figure 9). These data are consistent with the uniform flow rate of 0.01 m/s measured at four points near the shore of Upper Lyman by Carleton Geology students in the fall of 2004 (Brown, et. al., 2004). However, they tell us little about the overall mixing dynamics of the lake besides the fact that water is indeed moving from the inlet to the outlet. Although time constraints prevented their execution in our study, dye tracing tests would provide a much fuller picture of the flow dynamics in Upper Lyman.

Another possible source of inflowing water is groundwater springs at the bottom of the lake. The level of the water table makes these springs a definite possibility. The elevation of the bottom floor of Facilities is 910 ft above sea level, and a hose fed by the groundwater sustained pressure up to 10 feet above the ground, meaning that the water table has a potential elevation of 920 ft. Because the bottom of Upper Lyman Lake lies at 892 ft (Figure 1), water released from its confines deep underground could easily make its way up through the bottom of the lake as a spring. We tried to measure the temperature of this groundwater by driving a permeable pipe into the lakebed of Upper Lyman near shore and lowering a probe into it. This yielded a reading of 3.2°C, which is inconsistent with our hypothesis that groundwater could be a source of greater heat for the lake bottom. However, we suspect that the groundwater may be much warmer than our reading. Yoshitake et. al. (2002) employ the following equation to estimate groundwater temperature from known average air temperature:

$$T_{groundwater} = (0.83)(T_{av}) + 3.7$$

The air temperature at Carleton has averaged 6.9 °C over the past six years (Carleton Weather Database), so we can expect the groundwater temperature to be close to 9.4°C, which would definitely be a source of heat for Upper Lyman Lake. In the future, we would like to repeat the pipe test in the middle of the lake, and we expect to find a warmer groundwater temperature there.

Another concept suggests that groundwater feeds Upper Lyman Lake: if it does, then the water should be warmer at the outlet than at the inlet. On both of our testing dates, this was the case: on 2/7/06, average temperature increased from 2.500°C near the inlet to 3.200°C near the outlet, and on 2/14/06, average temperature increased from 2.700°C near the inlet to 2.956 near the outlet (Table 2). As Figure 8 demonstrates, however, the average temperature does not increase smoothly from the inlet to the outlet. The large fluctuations in average temperature suggest its limitations as an indicator of overall water temperature and the need for further testing. In addition, the overall warming of lake water does not guarantee the presence of spring water, because sediments could also be the heat source. To determine the contribution of spring water to Upper Lyman with certainty, we would need to measure the difference between the discharge at the inlet and at the outlet. This is a possibility for further study.

Both errors in measurements and limited data cause uncertainty in our study of Upper Lyman Lake. Because our measurements of temperature involved pushing a rod down into the lake, we must have induced at least some vertical mixing. Also, ice-melt from the holes we created may have produced artificially low near-surface temperatures. Temperature findings were at times inconsistent between two different probes, as can be seen in the undulating isothermal cross section EW1 2/7 (Figure 5) (two groups, each with a different probe, measured at alternating points along the lake). Lastly, faulty probes may have given inaccurate readings, especially in our measurement of groundwater temperature. We would like to have gathered more data, especially to compare the inlet and outlet temperatures. In addition, time constraints prevented us from revisiting many of our testing locations – our data thus varies simultaneously over place and time, making definitive comparisons difficult. However, the temperature relationships that we found are largely consistent and not discredited by our data collection methods.

CONCLUSION

We have reached several conclusions regarding the temperature profile and lake mixing of Upper Lyman Lake. First, the water temperature clearly increases with depth, and this temperature gradient is steepest near the surface. Probable contributors to this gradient include the density of water, heat transfer to the ice, ice melting, sediment heat transfer, and groundwater heating. While the heterogeneity of temperature indicates that complete vertical mixing does not occur, convective currents due to heat transfer are a possible form of vertical mixing. Second, water flows through Upper Lyman at a relatively uniform rate from inlet to outlet. The most conspicuous source of water is Spring Creek, but groundwater springs at the bottom of the lake may also be an important source of water.

Why study lake mixing? While the implications for our study may not be immediately apparent, lake mixing processes affect both the distribution of nutrients within a lake, and the potential spread of pollutants. An understanding of lake dynamics is thus extremely pertinent to biological activity.

Our study of lake mixing provides a solid base for future research. We have gained a fairly comprehensive understanding of the temperature profile of ice-covered Upper Lyman, but opportunities for further study abound.

SUGGESTIONS FOR FURTHER STUDY

Several additional tests would refine our model of lake mixing in Upper Lyman. First of all, obtaining temperature measurements at more consistent and frequent intervals would reinforce our hypotheses. We would advise returning to the same collection points throughout on several occasions—perhaps over consecutive days. In addition, our flow rate measurements were taken lengthwise down the middle of the lake from inlet to outlet; a perpendicular cross section would reveal variations between the center and the sides of the lake. Further tests to measure both the difference in discharge from inlet to outlet and the groundwater temperature near the middle of the lake would clarify the influence of groundwater springs in Upper Lyman.

Lastly, a dye tracer test would provide invaluable information about the path that water takes as it moves throughout the lake. Werner Käss' comprehensive Tracing Techniques in Geohydrology (1998) is a valuable guide for those interested in performing tracer tests. This book can be obtained through the Inter-Library Loan system. He and others suggest the organic fluorescing dye Rhodamine WT for use in surface water tests (Käss 1998, Green). Before introducing the dye near the inlet, several preliminary background tests must be conducted to rule out external sources of Rhodamine WT (Green). In addition, students should contact Greg Kruse of the Department of Natural Resources (greg.kruse@dnr.state.mn.us) to inquire about a permit, and should seek permission from Carleton authorities.

ACKNOWLEDGMENTS

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APPENDIX

Location	Depth (cm)	Date	
		1/31/2006	2/7/2006
		Temp. (°C)	Temp. (°C)
A	0	2.3	0.3
	20		1.5
	40		1.9
	60	3.2	2.8
	80		3
	100		3.8
	120	4.3	4
B	0	2.2	
	10		0.9
	35	2.7	
C	0	1.9 to 3.3	0.6
D	0	0.8	-0.1
	5		0.1
	21	1.5	
E	0	0.8	0.1
	10	0.9	0.1
F	0		0.1
	6	1.7	
	20		0.2
H	4	0.7	

Table 5. Shoreline Temperature

Location	Depth (cm)	Temp. (°C)
NS1.a	20	1.2
	60	3.5
	110	4.0
	160	4.2
	210	4.8
	260	4.8
NS1.b	20	0.8
	60	3.5
	110	3.2
	160	4.9
	210	5.0
	255	5.0
NS1.c	20	0.8
	50	2.2
	100	4.0
	150	4.6
	200	4.8
	245	4.9
NS1.d	20	0.8
	70	2.9
	120	4.1
	170	4.8

Table 6. NS1 Temperature (2/7/2006)

Location	Depth (cm)	Temp. (°C)	Conductivity (mS)
NS4.a	10	0.2	0.8
	30	0.8	0.8
	50	1.2	0.8
	70	3.3	0.7
	80	3.6	0.7
NS4.b (=EW1.a)	10	0.3	0.379
	30	1.4	0.3725
	50	3.4	0.3792
	70	3.6	0.3992
	90	3.8	0.4071
	110	3.8	0.4217
	118	3.9	0.4217
NS4.c	10	0.3	0.5
	30	0.4	0.4
	50	0.9	0.4
	58	1.7	0.4

Table 7. NS4 Temperature and Conductivity (2/14/2006)

Location	Depth (cm)	Temp. (°C)	Conductivity (µS)
NS2.a	10	0.5	379.4
	30	1.0	382.8
	50	1.7	391.8
	70	2.6	401.0
	90	3.2	402.2
	110	3.6	425.0
	130	3.7	438.8
	150	3.9	442.5
	170	4.2	500.0
	190	4.4	515.0
NS2.b	10	-0.1	346.6
	30	-0.1	346.3
	50	0.5	350.8
	70	1.9	357.0
	90	3.3	396.1
	110	3.9	421.1
	130	4.2	478.0
	150	4.5	519.0
	170	4.8	575.0
	190	4.8	606.0
	210	4.9	621.0
	230	4.9	631.0
	238	4.9	594.0
NS2.c	10	0.6	407.0
	30	0.6	408.4
	50	1.4	413.1
	70	2.3	421.2
	90	3.3	438.4
	110	3.9	487.0
	130	4.3	532.0
	150	4.5	578.0
	170	4.7	604.0
	190	4.9	640.0
	210	5.0	645.0
NS2.d	10	0.3	385.0
	30	0.6	
	50	1.5	416.0
	70	2.0	424.0
	90	2.7	433.6
	110	3.6	478.0
	130	3.9	510.0
	150	4.2	565.0
	170	4.8	626.0
	190	4.9	638.0
	210	5.2	643.0
NS2.e	10	0.1	391.0
	30	0.2	394.1
	50	1.2	411.5
	68	1.6	420.0

Table 8. NS2 Temperature and Conductivity (2/9/2006)

Location	Depth (cm)	Temp. (°C)	Conductivity (mS)
NS3.a	10	0.1	0.3
	30	0.3	0.4
	50	1	0.4
	70	1.8	0.4
	90	2.4	0.4
	110	3.1	0.4
	130	3.8	0.4
	140	3.9	0.4
NS3.b	10	0.1	0.3
	30	0.6	0.3
	50	1.5	0.3
	70	2.1	0.3
	90	2.7	0.3
	110	3.4	0.4
	130	3.9	0.4
	150	4.4	0.5
	170	4.6	0.5
	182	4.7	0.5
NS3.c (=EW1.c)	10	0.2	0.3349
	30	0.7	0.3443
	50	2.7	0.3729
	70	3.4	0.382
	90	3.4	0.3915
	110	3.6	0.4217
	130	3.8	0.4457
	150	4.3	0.493
	170	4.8	0.533
	190	4.9	0.541
NS3.d	10	0.2	0.3
	30	0.4	0.3
	50	1.4	0.3
	70	2.6	0.3
	90	2.9	0.3
	110	3.4	0.4
	130	4.1	0.4
	150	4.5	0.5
	170	4.7	0.5
	190	4.8	0.5
	210	4.9	0.5
NS3.e	10	0.4	0.3
	30	0.6	0.3
	50	1.8	0.3
	70	2.5	0.3
	90	2.9	0.3
	110	3.4	0.4
	130	3.7	0.4
	137	3.7	0.4

Table 9. NS3 Temperature and Conductivity (2/14/2006)

		Date		
		2/7/2006	2/14/2006	
Location	Depth (cm)	Temp. (°C)	Temp. (°C)	Conductivity (mS)
EW1.z	10		0.5	0.2
	30		3	0.3
	50		3.6	0.3
	65		3.7	0.3
EW1.a	0	-0.1		
	10	0.9	0.3	0.379
	30	2.1	1.4	0.3725
	50	3.5	3.4	0.3792
	70	3.7	3.6	0.3992
	90	3.8	3.8	0.4071
	110	3.6	3.8	0.4217
	118		3.9	0.4217
EW1.b	0	1.4		
	10	2.6	0.3	0.3296
	30	3.2	0.7	0.3403
	50	3.8	1.8	0.3726
	70	3.9	3.2	0.3909
	90	3.9	3.5	0.3969
	110	4.1	3.6	0.4136
	130	4.2	4.1	0.4546
EW1.c	10		0.2	0.3349
	20	1.2		
	30		0.7	0.3443
	50	2.7	2.7	0.3729
	70		3.4	0.382
	90		3.4	0.3915
	100	4.0		
	100	4.2		
	110		3.6	0.4217
	130		3.8	0.4457
	150	5.0	4.3	0.493
	170		4.8	0.533
	190	5.0	4.9	0.541
	200	4.7		
EW1.d	0	-0.1		
	10	-0.1	0.6	0.3508
	30	0.1	0.8	0.3634
	50	1.0	2	0.3734
	70	2.0	2.6	0.3819
	90	3.7	3.1	0.3911
	110	3.9	3.4	0.4023
	130	4.5	4	0.4394
	150	4.7	4.5	0.514
	170	4.8	4.7	0.528
	190	4.9	5	0.549
	210	5.0	5	0.571
	220		5.1	0.567

Table 10. EW1 Temperature and Conductivity

		2/7/2006	2/14/2006	
Location	Depth (cm)	Temp. (°C)	Temp. (°C)	Conductivity (mS)
EW1.e	10		0.2	0.3
	20	1.0		
	30		0.2	0.3
	45	2.1		
	50		1.3	0.3
	70		2.5	0.3
	90	3.2	2.8	0.4
	110		3.4	0.4
	130		4	0.5
	140	4.4		
	150		4.4	0.5
	170		4.8	0.5
	190	4.9	4.9	0.6
	210		5	0.6
	220		5	0.6
	235	5.0		
EW1.f	10	0.1	0.2	0.3
	30	0.2	0.6	0.3
	50	1.0	1.7	0.3
	70	1.8	2.4	0.3
	90	3.2	2.7	0.3
	110	3.6	3.6	0.4
	130	4.3	4.1	0.4
	150	4.6	4.4	0.5
	170	4.8	4.7	0.5
	190	4.8	4.8	0.5
	210	4.9	4.8	0.6
	230	4.9	4.9	0.6
	10		1	0.3
EW1.g	20	1.2		
	30		1.4	0.3
	40	2.0		
	50		1.8	0.3
	70		2.4	0.3
	90	3.8	2.8	0.3
	110		3.6	0.3
	130		3.9	0.4
	140	4.3		
	150		4.5	0.4
	170		4.7	0.5
	190	4.5	4.8	0.5
	210		4.9	0.5
	230		4.9	0.5
	240	4.7		
EW1.h	10		0.4	0.3
	20	1.3		
	30	1.8	0.7	0.4
	50	2.9	1.3	0.4
	70	3.2	2.1	0.4
	90	3.4	2.9	0.4

Table 10. continued

		2/7/2006	2/14/2006	
Location	**Depth (cm)**	**Temp. (°C)**	**Temp. (°C)**	**Salinity (mS)**
EW1.h cnt'd	110	3.9	3.3	0.4
	130	4.3	3.6	0.4
	150	4.5	4.2	0.5
	170	4.7	4.7	0.5
	190	4.8	4.8	0.5
	210	4.9	4.8	0.6
	225		4.8	0.6
	230	5.0		
EW1.i	10		0.8	0.3
	20	1.2		
	30		1.5	0.3
	40	2.1		
	50		1.9	0.3
	70		2.6	0.3
	90	3.3	2.9	0.4
	110		3.3	0.4
	130		3.6	0.4
	140	4.0		
	150		4.5	0.5
	170		4.7	0.5
	190	4.2	4.9	0.5
	190	4.4		
EW1.j	10		0.8	0.4
	30		1.6	0.4
	50		2.4	0.4
	70		2.9	0.4
	90		3.2	0.4
	110		3.5	0.4
	130		3.7	0.4
	150		4.2	0.5
	155		4.3	0.5

Table 10. continued