



THE STATE OF LAKE WOLSEY: WATER QUALITY DYNAMICS

Ngan Diep and Duncan Boyd

Environmental Monitoring and Reporting Branch
Water Monitoring and Reporting Section

Ontario Ministry of Environment and
Climate Change (MOECC)

2016

TABLE OF CONTENTS

1 Introduction and Objectives.....8

2 Materials and Methods.....9

 2.1 Survey Design and Study Area.....9

 2.2 Data Analysis.....15

3 Results & Discussion.....17

 3.1 Nutrients.....17

 3.1.1 Phosphorus.....17

 3.1.2 Nitrogen.....27

 3.2 Chlorophyll a.....28

 3.3 Water Chemistry.....33

 3.3.1 Dissolved Organic Carbon, Suspended Solids and Turbidity.....33

 3.3.2 Turbidity & Suspended Solids.....36

 3.3.3 Conductivity, Alkalinity and Chloride.....39

 3.3.4 Conductivity.....40

 3.4 Physical Structure.....43

 3.4.1 Bathymetry.....43

 3.4.2 Water Level.....45

 3.4.3 Thermal Structure.....47

 3.5 Dissolved Oxygen.....54

 3.5.1 Dissolved Oxygen: Real-time Monitoring.....54

 3.5.2 DO Depletion Rates.....63

 3.5.3 Dissolved Oxygen: Profiles and Volume-weight Averaged Concentrations.....63

 3.6 Vertical Profiles: Dissolved Oxygen Data.....66

4 Conclusions.....75

5 References..... 79

6 APPENDICES.....83

TABLE OF FIGURES

Figure 1 Map of Manitoulin Island, North Channel (● Lake Wolsey).....	11
Figure 2. Map of Lake Wolsey water quality stations (●) Environment Canada (EC) (●) Ministry of Environment and Climate Change (MOECC) and (●) Blue Goose /MTM Aquaculture.....	13
Figure 3 Map of Lake Wolsey real-time water quality sensor equipment stations,	15
Figure 4 Annual-averaged total phosphorus concentrations ($\mu\text{g L}^{-1}$), Lake Wolsey (MOECC data, 1986 – 2014).....	19
Figure 5 Total phosphorus ($\mu\text{g L}^{-1}$) frequency distribution curves for MOECC stations sampled in Lake Wolsey (N = 148; 1986 – 2014).....	20
Figure 6 Annual-averaged total phosphorus concentrations ($\mu\text{g L}^{-1}$), Lake Wolsey (Blue Goose/MTM Aquaculture annual water quality data, 1998 – 2014).....	22
Figure 7 Total phosphorus ($\mu\text{g L}^{-1}$) frequency distribution curves for for Blue Goose/MTM Aquaculture stations sampled in c) 1999 – 2003 and d) 2004 – 2014. Blue Goose/MTM Aquaculture data from the annual Water Quality Reports.....	23
Figure 8 Spatial map of all the MOECC stations (135) sampled for the Georgian Bay Water Quality Study in 2003 (●), 2004 (●) and 2005 (●) (from Diep et al, 2007).....	25
Figure 9 Total phosphorus concentrations ($\mu\text{g L}^{-1}$) as a function of Julian day over the ice-free season from April to October, Lake Wolsey (MOECC data, 2008 – 2011).....	26
Figure 10 Total phosphorus concentrations ($\mu\text{g L}^{-1}$) as a function of Julian day over the ice-free season, Lake Wolsey (Blue Goose/MTM Aquaculture, 1998 - 2004).....	27
Figure 11 Total phosphorus.....	27
Figure 13 Real-time continuous daily-averaged chlorophyll a (ppb) concentration through the ice-free season at 5 m below the water surface at A) Station 595 (2008) B) Station 596 (2008) C) Station 595 (2010) and D) Station 596 (2010). Arrows (→) indicate extracted samples taken by MOECC.....	31
Figure 13 Monthly in situ measurements of chlorophyll a (ppb) and turbidity (ppm) at the deep proximal site (Station 595) and near-cage site (Station 596) during the 2008 ice-free season, Lake Wolsey.....	32
Figure 15 Relationship between total phosphorus ($\mu\text{g L}^{-1}$) and chlorophyll a concentration ($\mu\text{g L}^{-1}$), Lake Wolsey, 2008—2010.....	32
Figure 16 The relationship between turbidity (ppm) and chlorophyll a (ppb) for A) Station 595 (deep site) and B) Station 596 (near-cage site) during the 2008 ice-free season, Lake Wolsey	33

Figure 18 Hourly-averaged real-time continuous <i>in situ</i> conductivity ($\mu\text{S cm}^{-1}$) trends through the 2010 ice-free season at 5 m below the water surface at A) Station 595 B) Station 596 C) Station 598.....	36
Figure 17 Daily-averaged real-time continuous <i>in situ</i> turbidity (ppm) trends through the ice-free season at 5 m below the water surface in 2008 at A) Station 595 B) Station 596 and in 2010 at C) Station 595 D) Station 596.....	39
Figure 24 Station 595 daily averaged temperature ($^{\circ}\text{C}$) with depth (m) and over time over the 2007 ice-free season.....	45
Figure 25 Daily averaged temperature ($^{\circ}\text{C}$) with depth (m) and over time for a) Station 595 and b) Station 596 over the 2008 ice-free season.....	45
Figure 26 Daily averaged temperature ($^{\circ}\text{C}$) with depth (m) and over time for a) Station 595 and b) Station 596 over the 2009 ice-free season.....	45
Figure 27 Daily averaged temperature ($^{\circ}\text{C}$) with depth (m) and over time for a) Station 595 and b) Station 596 over the 2010 ice-free season.....	45
Figure 28 Hypolimnetic depth (m) of the a) deep proximal site (Stn 595) from 2007 to 2009 and b) near-cage site (Stn 596) in 2008 and 2009, Lake Wolsey.....	47
Figure 29 Daily density differences between the hypolimnion and epilimnion for a) 2007 b) 2008 c) 2009 and 2010 ice-free season, Lake Wolsey.....	49
Figure 20 The relationship between the deep proximal site (Stn 595) and near-cage site (Stn..	50
Figure 21 Daily-averaged water level (m) at 3.0 m below water surface at Station 595 (deep site) during the ice-free season in 2008 and 2009, Lake Wolsey.....	51
Figure 22 Daily-averaged water level measurements at 4.0 m at the near-cage site (Station 596) during the 2008 ice-free season (May 30 – October 15, 2008), Lake Wolsey.....	51
Figure 23 Daily-averaged water level measurements at 3.0 m at the near-cage site (Station 596) during the 2009 ice-free season (June 06 – November 02, 2009), Lake Wolsey.....	51
Figure 19 Bathymetry map of Lake Wolsey, in one-meter, based on the 2006 MOECC/MNRF Bathymetry Study. Line indicates the 15 m (--) and 20 m (--) depth contours.....	53
Figure 30 Dissolved oxygen (mg L^{-1}) trends at Station 595 at a) 16.8 m and b) 20.8 m during the 2007 ice-free season, Lake Wolsey.....	57
Figure 31 Dissolved oxygen (mg L^{-1}) trends at Station 595 at a) 5 m b) 15 m c) 17 m and d) 23 m during the 2008 ice-free season, Lake Wolsey.....	59
Figure 38 Mid-column (16 – 18 m) dissolved oxygen (mg L^{-1}) concentration Stations a) 595 b) 596 c) 598 and d) 229 during the 2011 ice-free season, Lake Wolsey.....	60

Figure 39 Bottom-water (21 m) dissolved oxygen (mg L^{-1}) concentration Station 595 during the 2011 ice-free season, Lake Wolsey.....	61
Figure 40 Bottom-water (21 – 22 m) dissolved oxygen (mg L^{-1}) concentrations at Station 595 during the ice-free season from 2007 to 2010, Lake Wolsey.....	62
Figure 41 Dissolved oxygen depletion rates for real-time continuous sensors deployed in the bottom waters of Lake Wolsey (~ 22m), 2007 – 2010.....	62
Figure 42 Dissolved oxygen concentration (mg L^{-1}) as a function of time in a) 2007 b) 2008 c) 2009 and d) 2010, Lake Wolsey.....	63
Figure 43 The relationship between volume-weighted epilimnetic and metalimnetic water temperature ($^{\circ}\text{C}$) during the ice-free season from 1986 to 2009.....	64
Figure 44 Volume-weighted average water temperature ($^{\circ}\text{C}$) in the a) epilimnion b) metalimnion and c) hypolimnion during the ice-free season from 1986 to 2009, Lake Wolsey.....	66
Figure 45 Hypolimnetic thickness (m) as a function of time (Julian Day) from 1986 to 2009, Lake Wolsey.....	66
Figure 46 Volume-weighted epilimnetic, metalimnetic and hypolimnetic dissolved oxygen concentration (mg L^{-1}) 2005, Lake Wolsey.....	67
Figure 47 Volume-weighted average epilimnetic dissolved oxygen concentration (mg L^{-1}) of during the ice-free season, stations sampled in 2005.....	68
Figure 48 Volume-weighted average epilimnetic dissolved oxygen concentration (VWEDO) (mg L^{-1}) during the ice-free season from 1986 to 2014, Lake Wolsey.....	69
Figure 49 Volume-weighted average metalimnetic dissolved oxygen concentration (VWMDO) (mg L^{-1}) during the ice-free season from 1986 to 2014, Lake Wolsey.....	70
Figure 50 Volume-weighted average hypolimnetic dissolved oxygen concentration (VWHDO) (mg L^{-1}) during the ice-free season from 1986 to 2014, Lake Wolsey.....	70
Figure 51 Dissolved oxygen (mg L^{-1}) and temperature ($^{\circ}\text{C}$) with depth profile taken in Lake Wolsey on September 15, 2015.....	71
Figure 52 Volume-weighted average hypolimnetic dissolved oxygen concentration (VWHDO; mg L^{-1}) depletion rates between 2002 to 2014, Lake Wolsey.....	72
Figure 53 Relationship between volume-weighted averaged (VW) hypolimnetic dissolved oxygen (mg L^{-1}) and VW hypolimnetic temperature, 1986 – 2014, Lake Wolsey.....	73
Figure 54 Relationship between volume-weighted average (VW) metalimnetic and VW hypolimnetic dissolved oxygen (mg L^{-1}), 1986 – 2014, Lake Wolsey.....	74
Figure 55 Volume-weight averaged hypolimnetic dissolved oxygen concentration (mg L^{-1}) normalized to 4°C as a function of time (Julian day), Lake Wolsey.....	74

LIST OF TABLES

Table 1 Coordinates for MOECC ¹ , Environment Canada ² and Blue Goose / MTM Aquaculture ³ water quality sampling stations, Lake Wolsey.....	13
Table 2 Annual-averaged total phosphorus concentrations ($\mu\text{g L}^{-1}$), Lake Wolsey (MOECC data, 1986 – 2014).....	18
Table 2 Annual-averaged total phosphorus concentrations ($\mu\text{g L}^{-1}$), Lake Wolsey (Blue Goose/MTM Aquaculture, 1998 - 2014).....	20
Table 3 Seasonal phosphorus concentrations ($\mu\text{g L}^{-1}$) for stations sampled by by the Ontario Ministry of Environment (MOECC; 1986-2011), Environment Canada (EC; 2009) and Blue Goose /MTM Aquaculture (1998-2014).....	23
Table 4 Summary of hypolimnetic nutrient concentrations for sites samples in Lake Wolsey between 2008—2011.....	27
Table 5 Summary of epilimnetic water chemistry data for sites samples in Lake Wolsey from 2008 to 2010.....	34
Table 6 Summary of epilimnetic water chemistry data for sites samples in Lake Wolsey, 2011	35
Table 7 Summary of hypolimnetic water chemistry data for sites samples in Lake Wolsey from 2008 to 2011.....	38
Table 8 Summary of the stratification features of the deep proximal site (Stn 595) and near-cage site (Stn 596) based on the real-time continuous <i>in situ</i> temperature ($^{\circ}\text{C}$) data collected between 2007 to 2009, Lake Wolsey.....	48
Table 9 Dissolved oxygen concentration (mg L^{-1}) for Station 595, 596, 229 and 598 for the ice-free season between 2007—2010.....	55
Table 10 Volume-weighted average hypolimnetic dissolved oxygen depletion rates ($\text{mg L}^{-1} \text{ day}^{-1}$; $\text{mg L}^{-1} \text{ month}^{-1}$) during the ice-free season from 1986 to 2014, Lake Wolsey.....	72

LIST OF APPENDICE

APPENDIX 1 Summary of epilimnetic nutrient and chlorophyll a concentrations, Lake Wolsey (2008 – 2010)..... 85

APPENDIX 2 Summary of epilimnetic nutrient and chlorophyll a concentrations in 2011, Lake Wolsey..... 86

APPENDIX 3 Dissolved oxygen (mg L^{-1}) trends at Station 596 at a) 5 m b) 15 m and c) 17 m during the 2008 ice-free season, Lake Wolsey..... 87

APPENDIX 4 Dissolved oxygen (mg L^{-1}) trends at Station 595 at a) 5 m b) 15 m c) 17 m and d) 22 m during the 2009 ice-free season, Lake Wolsey..... 88

APPENDIX 5 Dissolved oxygen (mg L^{-1}) trends at Station 596 at a) 5 m b) 15 m and c) 17 m during the 2009 ice-free season, Lake Wolsey..... 89

APPENDIX 6 Dissolved oxygen (mg L^{-1}) trends at Station 595 at a) 4.9 m b) 16.9 m and c) 21.9 m during the 2010 ice-free season, Lake Wolsey..... 90

APPENDIX 7 Dissolved oxygen (mg L^{-1}) trends at Station 596 at a) 5.7 m b) 15.7 m and c) 17.7 m during the 2010 ice-free season, Lake Wolsey..... 91

APPENDIX 8 Dissolved oxygen (mg L^{-1}) concentrations at Station 229 at a) 5.8 m and b) 17.8 m and at Station 598 at c) 6.0 m and d) 18.0 m during the 2010 ice-free season, Lake Wolsey 92

1 Introduction and Objectives

Lake Wolsey, an embayment located in the North Channel of the Great Lakes, has been identified as a waterbody sensitive to eutrophication and susceptible to hypolimnetic dissolved oxygen (DO) depletion (Gale, 1999; Hamblin and Gale, 2002; Clerk, 2001). There are no major tributaries flowing into Lake Wolsey and the culvert between Lake Wolsey and North Channel/Great Lakes waters is the only outflow (Milne et al., 2015). According to the water body classification system for siting aquaculture cage facilities documented in Boyd et al. (2001) this is a Type 2 site with good flushing of surface water but with limited or no bottom-water exchange.

Hamblin and Gale (2002) previously flagged the potential for Lake Wolsey to experience water quality impairment given the presence of a cage aquaculture operation whose discharge has the potential to increase ambient P concentrations if production were to increase. In 2006, the Ontario Ministry of Environment and Climate Change (MOECC) documented severe hypolimnetic DO depletion with wide-spread hypolimnetic anoxia and observed a harmful algal bloom (cyanobacteria, also referred to as blue-green algae). These observations triggered: (a) a detailed, multi-year study to quantify spatial and temporal changes in water quality conditions; and (b) a land use based source loading estimation assessment to identify the greatest relative contributors of nutrient and BOD/organic materials to this embayment.

Since 2001 water quality monitoring by cage aquaculture operations has been required as part of the aquaculture licensing process following recommendations developed through a collaborative process between industry representatives, Georgian Bay Association, and technical staff from MOECC, Ontario Ministry of Natural Resources and Forestry (MNRF), Ontario Ministry of Agriculture Food and Rural Affairs (OMAFRA), and University of Guelph. This report uses these monitoring data for the Lake Wolsey operation, along with results from an Environment Canada lake-wide phosphorus survey, to augment data collected by the MOECC water quality monitoring program. It documents historical and recent limnological conditions with particular emphasis on the extent of the hypolimnetic DO depletion observed in this embayment and tracks changes in the environmental condition of Lake Wolsey over the period 1986 to 2014. It provides recent, detailed information on key water quality parameters including phosphorus, chlorophyll *a*, thermal structure and volume-weighted average hypolimnetic dissolved oxygen concentration and depletion rates. These data are used to

determine whether the adverse conditions observed in 2006 have persisted and demonstrates a prolonged shift in the trophic state of this waterbody.

Although this report documents the occurrences of algal blooms, it does not examine phytoplankton structure, food web dynamics or the causal factors driving the algal blooms. Observed water quality conditions will undoubtedly influence the taxonomy of phytoplankton and zooplankton, and hence the food web structure and productivity of the waterbody, but the analysis contained in this report is restricted to examination of the spatial and temporal extent of water quality impairment through comparison of results with Provincial Water Quality Objectives (PWQOs).

2 Materials and Methods

2.1 Survey Design and Study Area

Lake Wolsey is a large embayment, ~ 2203 ha (Milne et al, 2015), located on Manitoulin Island (Figure 1; 45 49' 22" N, 82 31 29" W), the largest freshwater island (712 000 acres) (Hoffman et al, 1959) situated in the North Channel of the Great Lakes. The mean depth of this embayment is 11.8 m and it possesses a large littoral zone fringed with wetlands on the northern shores. The littoral zone in the southern part of Lake Wolsey is heavily colonized with zebra mussels, particularly in the vicinity of the cage aquaculture operation (Hille, 2008). The deep basin of Lake Wolsey is located in the southwest portion of the embayment with a maximum water depth of 24 m. Although the culvert limits the exchange between Lake Wolsey and the open waters of the North Channel to the upper 4 m (Milne et al, 2015), the exchange between the two water bodies is typically high with an average volume exchange rate of $14 \text{ m}^3 \text{ s}^{-1}$ (Hamblin and Gale, 2002) and flow velocities of up to 1.5 m s^{-1} (Milne et al, 2015). Outflow is highest in the spring (Milne et al, 2015). Daily flow reversals are common in Lake Wolsey and this system is also influenced by wind conditions which can exceed 60 km h^{-1} (Milne et al., 2015). The residence time of Lake Wolsey has been estimated to be as low as 199 days (Milne et al, 2015) or as high as 215 days (Hamblin and Gale, 2002). It should be noted, however, that these estimates represent the flushing rate for upper surface waters (Milne et al, 2015).

In 2006, the MOECC and MNRF took over 47,000 depth sounding readings over the entire surface of Lake Wolsey and the coordinates were differentially corrected to sub-metre accuracy. These data were used to update the bathymetry of Lake Wolsey for use in this report .

MOECC has monitored water quality at stations located throughout Lake Wolsey (Stn 235 – 238, 229, 595 and 596) with the majority of monitoring occurring within the deep basin (> 15 m) (Figure 2, Table 1). Additional water quality data are available for sites throughout the embayment collected by Environment Canada (EC) in 2009 (Figure 2).

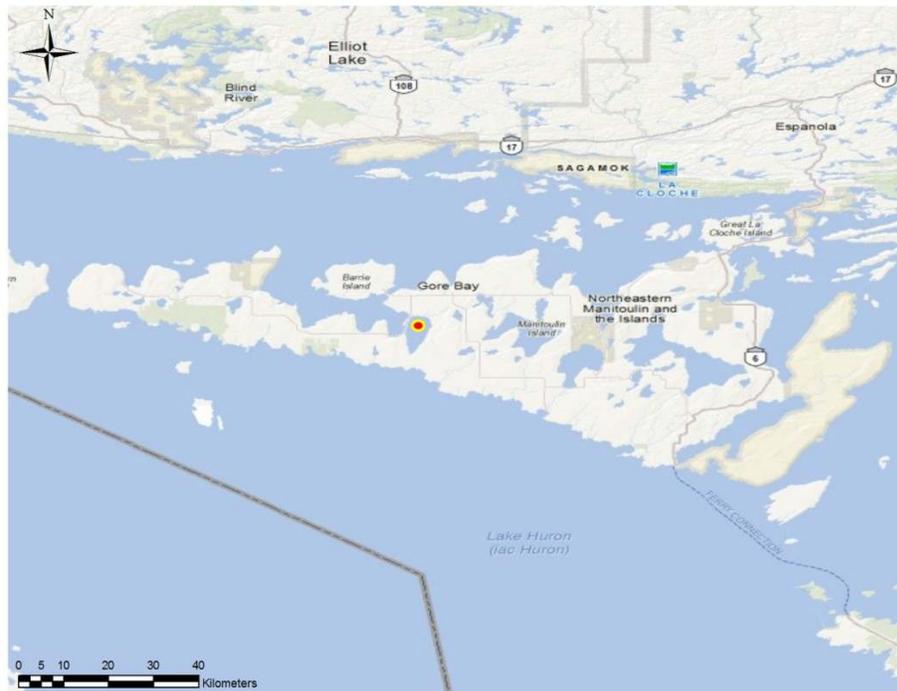


Figure 1 Map of Manitoulin Island, North Channel (• Lake Wolsey)

As part of the aquaculture licencing process Blue Goose / MTM aquaculture monitors the water quality in the immediate vicinity of the cage aquaculture operation, at the proximal deep station sites and at a reference location. The near-cage stations are located primarily 30 m from the cage aquaculture operation (M01, M02 and M03) and the proximal deep stations are sited in the deep basin (M06, M07) (Figure 2, Table 1). The reference station (M05) is located 1 – 2 km north of the cage aquaculture facility and near the culvert (Figure 2, Table 1).

Over 350 *in situ* physical profiles of temperature and dissolved oxygen with depth were collected by the MOECC and Blue Goose / MTM Aquaculture during the ice-free season from 1986 to 2015. These profiles were used to characterize the physical structure of the water column in order to determine thermal stratification patterns, dissolved oxygen condition and to ground-truth the real-time continuous *in situ* measurements.

The MOECC collected water quality data to complement collection of real-time continuous monitoring over the period 2008 to 2011. Water samples were collected at all MOECC stations (Figure 2) in the spring, summer, and fall. Duplicate depth-integrated samples were taken from the surface to twice the secchi depth or to the top of the metalimnion, whichever was less. If the water body was thermally stratified and the presence of a hypolimnion was detected, a single grab sample of water was taken at 1m from the lake bottom with the Beta sampler. Samples were kept cool, in the dark and submitted to the MOECC Laboratory Services Branch for water quality analysis. Samples were analyzed for conductivity, chloride, dissolved organic carbon (DOC), total suspended solids (TSS), pH, total phosphorus, total kjeldahl nitrogen, ammonia, nitrite, nitrate, phosphate, calcium, magnesium, sodium, potassium, hardness, alkalinity and chlorophyll pigments (epilimnion only). Additional duplicate samples were submitted to the MOECC Dorset laboratory for low-level total phosphorus analysis. In addition to the intensive 2008-2011 sampling results, MOECC historical P data from Lake Wosley (1986) and P data from Environment Canada (2009) were also examined.

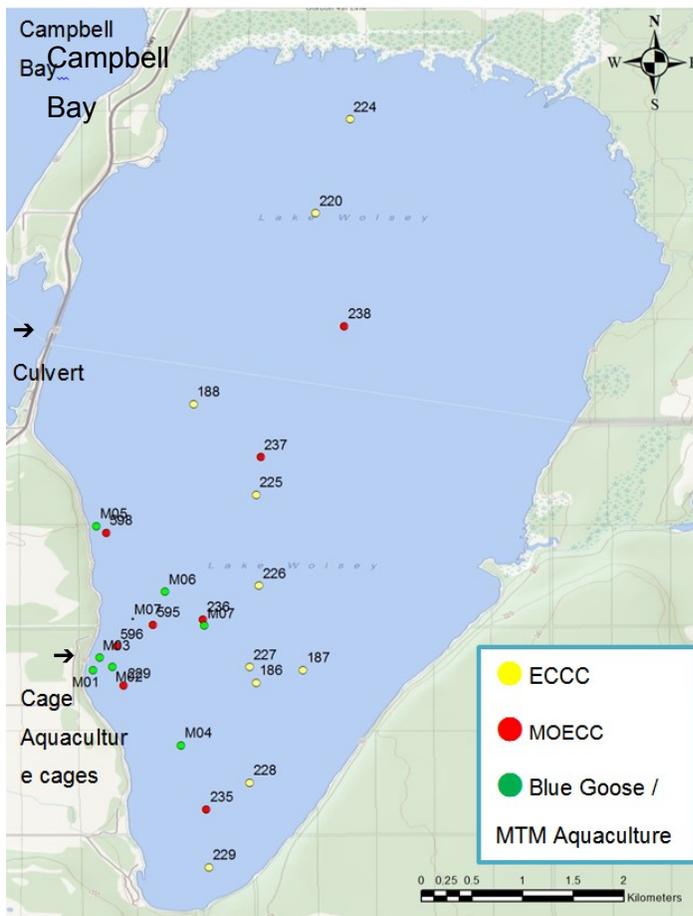


Figure 2. Map of Lake Wolsey water quality stations (●) Environment Canada (EC) (●) Ministry of Environment and Climate Change (MOECC) and (●) Blue Goose /MTM Aquaculture

Table 1 Coordinates for MOECC¹, Environment Canada² and Blue Goose / MTM Aquaculture³ water quality sampling stations, Lake Wolsey

Platform	Station		DD N	MM N	SS N	DD W	MM W	SS W	Easting	Northing
	Station No.	Description								
MOECC	235	NR-SP5	45	47	19.5	82	32	15.8	380478	5071726
MOECC	236	NR-SP4	45	48	20.2	82	32	17.0	380490	5073602
MOECC	237	NR-SP3	45	49	12.0	82	31	58.5	380912	5074858
MOECC	238	NR-SP2	45	49	53.9	82	31	31.8	381520	5076473
MOECC	595	Deep proximal	45	48	18.5	82	32	32.9	380145	5073554
MOECC	596	Near-cage	45	48	11.6	82	32	44.5	379890	5073346
MOECC	229	Near-cage	45	47	59.0	82	32	42.2	379932	5072956
MOECC	598	Near culvert	45	48	47.9	82	32	47.9	379838	5074468
MTM/Blue Goose	M01	Near-cage (south)	45	48	4.0	82	32	52.0	379724	5073115
MTM/Blue Goose	M02	Near-cage (east)	45	48	5.0	82	32	46.0	379854	5073143
MTM/Blue Goose	M03	Near-cage (north)	45	48	8.0	82	32	50.0	379769	5073237
MTM/Blue Goose	M04	South reference	45	47	40.0	82	32	24.0	380314	5072362
MTM/Blue Goose	M05	North reference	45	48	50.0	82	32	51.0	379773	5074534
MTM/Blue Goose	M06	Deep proximal	45	48	29.0	82	32	29.0	380235	5073877
MTM/Blue Goose	M07	Deep proximal	45	48	18.2	82	32	16.6	380497	5073539
Environment Canada	220		45	50	30.0	82	31	41.0	381343	5077591
Environment Canada	224		45	50	60.0	82	31	30.0	381597	5078512
Environment Canada	225		45	49	0.0	82	32	0.0	380879	5074821
Environment Canada	226		45	48	31.0	82	31	59.0	380884	5073926
Environment Canada	227		45	48	5.0	82	32	2.0	380804	5073125
Environment Canada	228		45	47	28.0	82	32	2.0	380782	5071983
Environment Canada	229		45	47	1.0	82	32	15.0	380485	5071155
Environment Canada	186		45	48	0.0	82	32	0.0	380844	5072970
Environment Canada	187		45	48	4.0	82	31	45.0	381170	5073087
Environment Canada	188		45	49	29.0	82	32	20.0	380465	5075725
Environment Canada	189		45	50	1.0	82	33	50.0	378542	5076750

¹ Ontario Ministry of Environment and Climate Change (MOECC)² Environment Canada data from NAR (2010)³ Data from MTM/Blue Goose aquaculture annual water quality reports

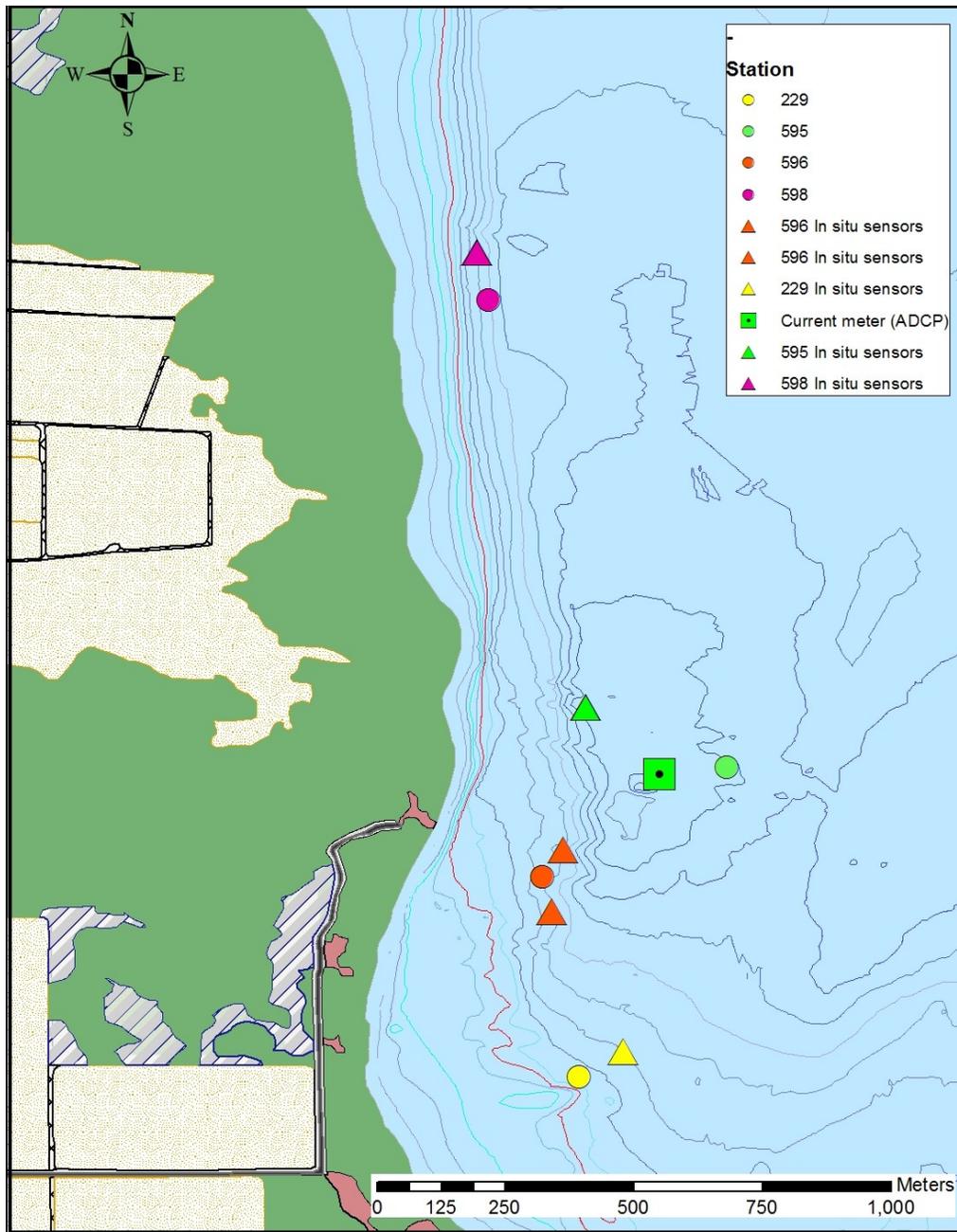


Figure 3 Map of Lake Wolsey real-time water quality sensor equipment stations, (--) line indicates the 15 m depth contour

Between 2007 and 2011 the MOE deployed a suite of real-time continuous *in situ* water quality sensors throughout the water column in Lake Wolsey (Figure 3) to track changes in the physical structure of the water column. *In situ* water quality sensors were deployed in the spring and retrieved in the late fall to characterize conditions during the ice-free season. Dissolved oxygen sensors were deployed at all stations (Table 1) and continuously logged dissolved oxygen and

temperature at 10 minute intervals. At each station these were deployed near-surface (~4 to 5m), mid-water column depth (~15 to 17m) and near-bottom (~ 22m) to capture epilimnetic, metalimnetic and hypolimnetic thermal and dissolved oxygen conditions.

On each DO sensor equipment chain, Onset Stowaway temperature tidbits were attached in 1 to 3m increments from the water surface to bottom. These sensors continuously logged temperature at 10 minute intervals. HOBO water level loggers with temperature were deployed on all DO sensor equipment chains and continuously logged at 30 minute intervals. For select stations and years, turbidity and chlorophyll *a* sensors were also deployed ~ 5m below the water surface and continuously logged water temperature, turbidity and chlorophyll *a* at 30 minute intervals.

2.2 Data Analysis

The real-time continuous *in situ* sensors generated large amounts of environmental information. Data quality was checked and verified using relevant equipment software applications, Excel 2003 and Systat 12. The real-time continuous data were averaged hourly, daily and monthly using SYSTAT 12. All data graphs were generated using SYSTAT 12 and maps were generated using ArcView 9.1.

Lake Wolsey depth sounding data collected in 2006 were converted into a triangulated irregular network (TIN) and grid in order to determine the area and volume of each depth strata, according to the elevation or height above sea level data. An updated bathymetry map using ArcGIS 9.1, in one-meter increments, was then generated for Lake Wolsey.

To facilitate the analysis of the over 350 temperature and dissolved oxygen depth profiles summary statistics (e.g., minimum, maximum) were generated for each of the profiles along with graphs which were plotted using Sigmaplot. For each *in situ* physical profile we generated a density profile to determine objectively if the water column was stratified using the following equation:

$$\text{Equation 1: Density} = [1000 \times (1 - (T + 288.9414))] / (508929.2 \times (T + 68.12963)) \times (T - 3.9863)^2$$

If the presence of a hypolimnion or metalimnion was detected, the thermal boundaries (i.e., epilimnetic, metalimnetic and hypolimnetic depths) were determined to calculate volume-

weighted averages for temperature and dissolved oxygen for each of the water masses. Near-surface (<0.5m) temperature and dissolved oxygen data were excluded from the analysis to prevent near-surface warming from resulting in an artificially shallow metalimnion. The physical profile vertical resolution varied between years, depending on the data source, with dissolved oxygen depth being recorded in 1 or 2 m increments or continuously through the water column. After the thermal boundaries were calculated the data were collapsed into one metre resolution, as recommended by Quinlan *et al* (2010) if the depth resolution was high, or interpolated between depths if the depth resolution was low.

If a strong density gradient was observed (i.e. where the relative difference between surface water density and the water density at the maximum profile depth was 2.0) the density criteria was set to 0.50 and 0.75 for the upper and lower metalimnetic boundaries, respectively. This was used to offset the proportionally small difference at the water surface which can lead to artificially shallow metalimnetic boundaries. If the density range was less than 2.0, then the upper and lower metalimnetic boundary density criteria were set to 0.25 and 0.50, respectively. The upper and lower limits represent the top and bottom of the metalimnion and hence represent the bottom of the epilimnion and top of the hypolimnion, respectively.

The volume-weighted epilimnetic, metalimnetic and hypolimnetic temperature and dissolved oxygen concentrations were then calculated for all the profiles. Each depth stratum was categorized according to water mass type (i.e., epilimnion, metalimnion or hypolimnion). If the thermal boundary fell between two depths, the volume was divided according to the depth demarcation. The surface area and volume for each depth stratum (e.g., 2 to 3m, 3 to 4m etc) was determined using the Lake Wolsey 2006 bathymetry and area data and the total volume and surface area for the epilimnion, metalimnion and hypolimnion were then calculated based on the location of the thermal boundaries. The average temperature and dissolved oxygen for each 1m depth stratum within each water mass was multiplied by the volume of that stratum and divided by the total volume of the relevant water mass. Summing these products for the strata in each water mass yields the volume-weighted temperature or dissolved oxygen concentration. The same approach was used to calculate the thermal boundaries based on the real-time continuous *in situ* temperature data for 2007 to 2011.

3 Results & Discussion

3.1 Nutrients

3.1.1 Phosphorus

Phosphorus is a limiting nutrient in temperate freshwater ecosystems and is a major determinant in the productivity of the system (Wetzel, 2001). The trophic status of waterbodies is typically determined by ambient total phosphorus (P) concentrations where P concentrations between 4 and 10 $\mu\text{g l}^{-1}$ and 10 and 20 $\mu\text{g l}^{-1}$ indicate oligotrophic and mesotrophic conditions, respectively. P levels in excess of 20 $\mu\text{g l}^{-1}$ are indicative of eutrophic conditions (CCME, 2004). The MOECC has identified two interim Provincial Water Quality Objectives (PWQOs) of 10 $\mu\text{g l}^{-1}$ and 20 $\mu\text{g l}^{-1}$, respectively for protection against aesthetic deterioration and to avoid nuisance concentrations of algae (MOE, 1994). Historical and recent phosphorus (P) data from the MOECC indicate conditions ranging from oligotrophic to mesotrophic conditions based on annual-averaged P concentrations, exceeding the PWQO of 10 $\mu\text{g l}^{-1}$ between 1998 – 2010 (Figure 4, Table 2). P concentrations ranged from 3 $\mu\text{g l}^{-1}$ to 24 $\mu\text{g l}^{-1}$ and followed a seasonal pattern with significant increases in P concentrations over the ice-free season (Error: Reference source not found, Error: Reference source not found). When phosphorus concentration was plotted over time or Julian Day, there was a significant increase in P concentrations over the ice-free season ($P < 0.05$, Mann-Kendall test) with P concentrations increasing to levels above 10 $\mu\text{g/L}$ in the summer and fall.

In 2009, Environment and Climate Change Canada (ECCC) sampled 9 locations within the Lake Wolsey area (NAR, 2010). Their results were consistent with the MOECC data with P values falling within the same range ($\sim 6 - 14 \mu\text{g l}^{-1}$) as the MOECC data for 2009. Their annual-averaged P concentration of 9 $\mu\text{g l}^{-1}$ is lower likely due to the sampling survey being constrained to the spring season ().

We compared recent (post-2004) and historic (pre-2004) P concentrations and found they were not significantly different ($p = 0.845$, Mann-Whitney U Test; MOECC data only), indicates P levels in Lake Wolsey have not changed significantly over time.

Overall, lake-wide P conditions were generally homogeneous with surface water P levels generally consistent between stations for a given season and year. Although between-station variability was low, with P levels typically within 2 $\mu\text{g l}^{-1}$ of each other, some inter-annual

variability was evident. Annual-averaged P concentrations varied between years, with the 1980s and 2014 representing the low-end of the P spectrum. Annual-averaged P concentrations generally decreased between 2008 and 2014 and this is similar to Milne et al's (2015) observation for the 2001 to 2009 period. The frequency distribution curve for the P dataset reveal a bimodal distribution with one peak in the oligotrophic range ($< 10 \mu\text{g L}^{-1}$) and the second peak in the mesotrophic range, between 10 and 15 $\mu\text{g L}^{-1}$.

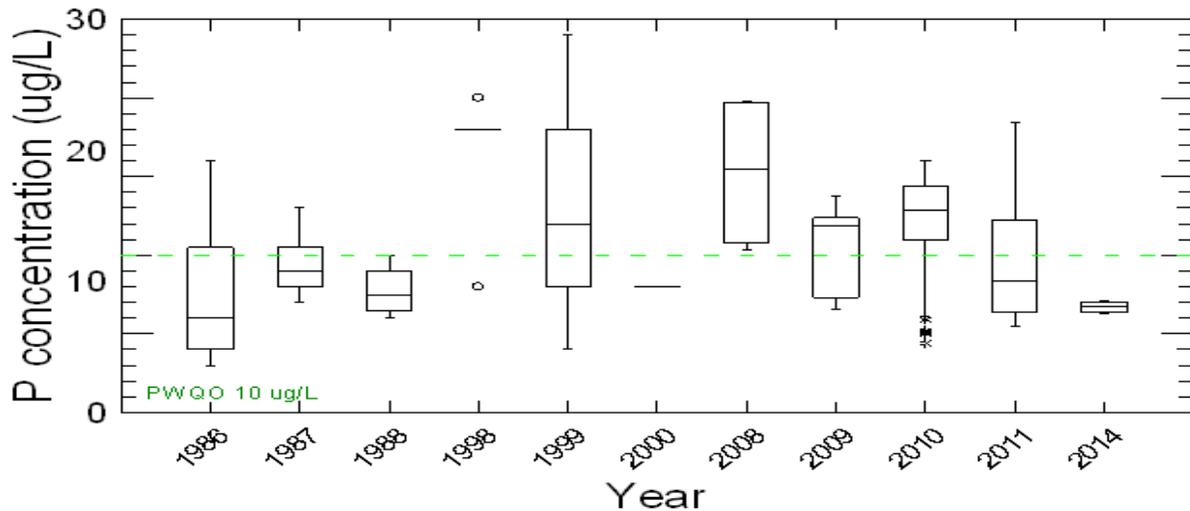


Figure 4 Annual-averaged total phosphorus concentrations ($\mu\text{g L}^{-1}$), Lake Wolsey (MOECC data, 1986 - 2014)

Table 2 Annual-averaged total phosphorus concentrations ($\mu\text{g L}^{-1}$), Lake Wolsey (MOECC data, 1986 - 2014)

Year	N	Mean	Median	Min.	Max.	Std Error	Std Deviation	CV
1986	8	7.5	6.0	3.0	16.0	1.592	4.504	0.601
1987	8	9.4	9.0	7.0	13.0	0.706	1.996	0.213
1988	8	7.8	7.5	6.0	10.0	0.526	1.488	0.192
1998	5	16.4	18.0	8.0	20.0	2.135	4.775	0.291
1999	33	13.6	12.0	4.0	24.0	1.06	6.092	0.447
2000	1	8.0	8.0	8.0	8.0			
2008	6	15.3	15.5	10.3	19.8	1.727	4.229	0.277
2009	18	10.6	11.9	6.6	13.8	0.637	2.703	0.256
2010	33	11.5	12.9	4.4	16.0	0.622	3.576	0.31
2011	24	9.8	8.3	5.5	18.4	0.835	4.091	0.418
2014	4	6.7	6.7	6.3	7.1	0.204	0.408	0.061

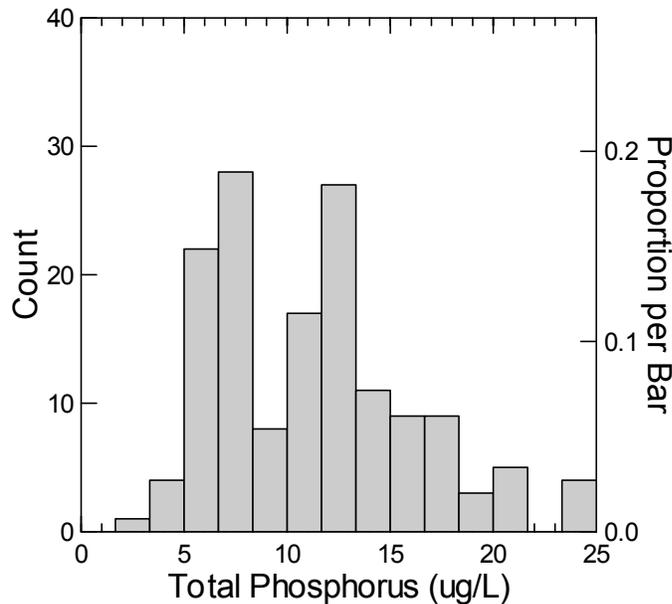


Figure 5 Total phosphorus ($\mu\text{g l}^{-1}$) frequency distribution curves for MOECC stations sampled in Lake Wolsey (N = 148; 1986 - 2014)

We examined the P dataset from Blue Goose/MTM Aquaculture annual water quality monitoring reports and found conditions extended into the eutrophic range. Figure 7 is a summary graph of P concentration over time. Although annual-averaged P concentration was as high as 15 $\mu\text{g/L}$ in 1998, for the most part P levels were at or below 10 $\mu\text{g/L}$ between 1999 to 2003 and is indicative of oligotrophic conditions. 2004 to 2012 results from the annual water quality monitoring report indicate exceedances of the PWQO of 10 $\mu\text{g/L}$ which indicates a change to mesotrophic conditions, however values fell below the objectives in 2013 and 2014. Annual-averaged P concentrations ranged from 7 to 27 $\mu\text{g l}^{-1}$, with maximum concentrations above 40 $\mu\text{g/L}$. We found these values to be significantly higher than the MOECC results ($p \leq 0.01$, ANOVA). The maximum P concentration of 64 $\mu\text{g l}^{-1}$ observed in the Blue Goose/MTM Aquaculture dataset (excluding the 150 $\mu\text{g l}^{-1}$ datapoint) is nearly 3-fold higher compared to the MOECC P maximum of 24 $\mu\text{g l}^{-1}$.

Prior to 2004, data from Blue Goose / MTM Aquaculture self-monitoring indicated oligotrophic to eutrophic conditions with values ranging from 4 to 30 $\mu\text{g l}^{-1}$ with a median P of 9 $\mu\text{g l}^{-1}$ (N=259) and maximum P levels observed in the spring (Error: Reference source not found). However more recent self-monitoring data (2004 to 2014) indicate conditions ranged from ultra-oligotrophic to hypereutrophic with P concentrations from 1 $\mu\text{g l}^{-1}$ to 150 $\mu\text{g l}^{-1}$ ().

Table 3 Annual-averaged total phosphorus concentrations ($\mu\text{g L}^{-1}$), Lake Wolsey (Blue Goose/MTM

Aquaculture, 1998 - 2014)

Year	N	Mean	Median	Min.	Max.	Std Error	Std Deviation	CV
1998	24	15.0	14.3	6.0	19.0	0.82	4.03	0.28
1999	17	10.0	11.2	8.0	21.0	0.79	3.27	0.29
2000	32	8.0	8.6	4.0	30.0	0.83	4.71	0.55
2001	54	9.0	9.6	6.0	14.0	0.26	1.91	0.20
2002	66	9.0	9.0	7.0	12.0	0.16	1.27	0.14
2003	66	10.5	10.6	8.0	14.0	0.19	1.53	0.15
2004	40	20.5	21.0	13.0	42.5	0.82	5.21	0.25
2005	57	13.0	13.2	2.0	45.0	1.09	8.24	0.62
2006	57	13.0	13.2	2.0	45.0	1.09	8.24	0.62
2007	55	27.1	24.4	2.0	50.5	1.72	12.78	0.52
2009	60	16.0	17.3	2.0	64.1	1.63	12.65	0.73
2010	56	11.0	14.4	1.6	50.3	1.37	10.28	0.72
2011	66	14.0	14.9	1.0	28.0	0.89	7.24	0.49
2012	66	13.0	11.3	1.0	32.0	1.01	8.23	0.73
2013	60	9.0	9.9	2.0	33.0	0.68	5.25	0.53
2014	66	6.7	7.2	2.0	20.3	0.49	3.94	0.55

To better understand the discrepancy between the datasets, we compared data from ECCC, Blue Goose/MTM Aquaculture and MOECC based on May/June 2009 data. We found the Blue Goose/MTM Aquaculture results were significantly higher ($p \leq 0.01$, ANOVA) with an early season (spring) average concentration of $29 \mu\text{g l}^{-1}$ compared to $6 \mu\text{g l}^{-1}$ observed by ECCC/MOECC. This significant difference ($p \leq 0.01$, ANOVA) between the MOECC and Blue Goose/MTM Aquaculture datasets is also observed in 2011, but not from the 1997-2000 or the 2014 results. We were unable to make a comparison for 2001 – 07 and 2012 -13 as the datasets did not overlap. The elevated P concentration could be explained as an artefact of the survey design, as the majority of the Blue Goose/MTM Aquaculture sampling sites are located in the immediate vicinity (30 m) of the cage aquaculture operation and therefore may be in the nearfield plume; however results from the reference sites were consistent with the aquaculture sampling stations. When we examined the distribution curves for data collected by Blue Goose/MTM Aquaculture, we find that post 2004, the distribution curve is skewed to the left with a long right tail. Based on the 2009 comparison, we concluded that this dataset represents an overestimation of P levels in Lake Wolsey, likely from 2004 onwards where P concentrations are observed to above the 35 ug/L trigger range for meso-eutrophic conditions (CCME, 2004), and any analysis or use of this data should be evaluated judiciously.

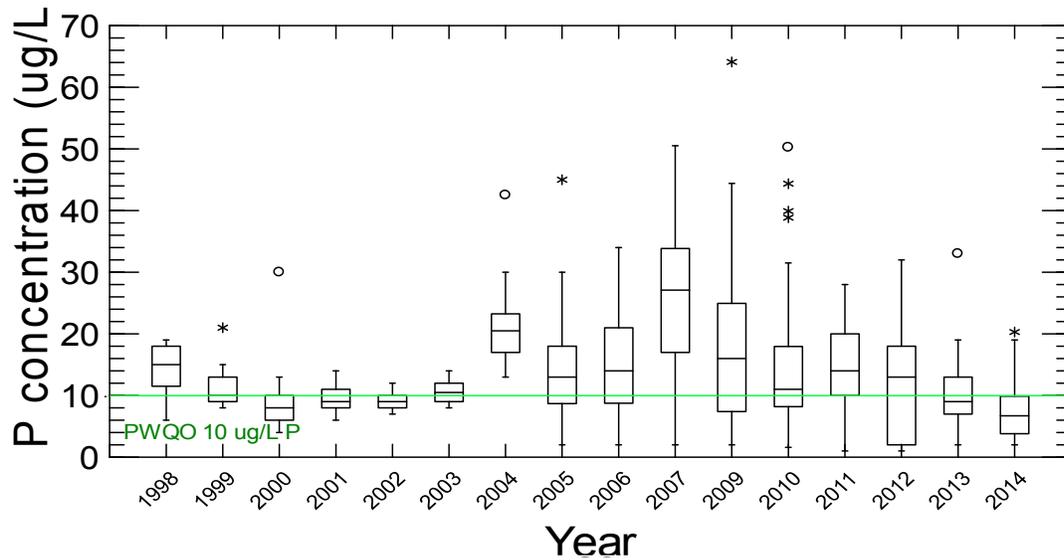


Figure 6 Annual-averaged total phosphorus concentrations ($\mu\text{g L}^{-1}$), Lake Wolsey (Blue Goose/MTM Aquaculture annual water quality data, 1998 - 2014)

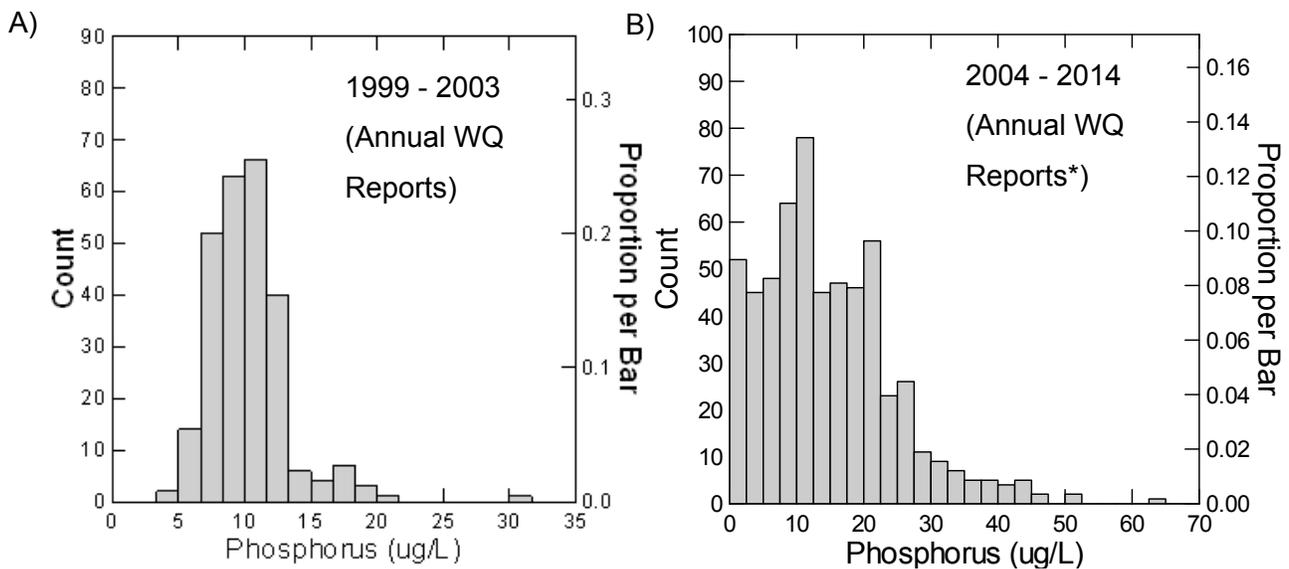


Figure 7 Total phosphorus ($\mu\text{g L}^{-1}$) frequency distribution curves for for Blue Goose/MTM Aquaculture stations sampled in c) 1999 - 2003 and d) 2004 - 2014. Blue Goose/MTM Aquaculture data from the annual Water Quality Reports

* Blue Goose/MTM Aquaculture phosphorus concentration of $150 \mu\text{g L}^{-1}$ at near-cage station (MA2) on September 20, 2010 is not included

There is a distinct seasonality component with low P concentrations in the spring, typically in the oligotrophic range and below the PWQO of $10 \mu\text{g L}^{-1}$ and increasing over the ice-free season to seasonal averages in the mesotrophic range ($10 - 20 \mu\text{g L}^{-1}$). This seasonal pattern was observed in all datasets (). For most water bodies unaffected by seasonal anthropogenic

inputs P concentrations are typically highest in the spring and hence spring P is often used to determine the trophic status of the water body (CCME, 2004). A study examining the water quality conditions of 135 locations within Georgian Bay nearshore areas (Figure 8) found maximum P levels in the spring, reflecting the greatest watershed influence following spring freshet, with a slight decline over the summer and fall (Error: Reference source not found⁵) (Diep et al, 2007). For this study the majority of the Georgian Bay stations exhibited oligotrophic conditions ($< 10 \mu\text{g L}^{-1}$) (Figure 55), P levels were found to exceed the interim PWQO of $20 \mu\text{g L}^{-1}$ at shallow, turbid stations or stations in well-developed high-DOC embayments (Diep et al, 2007). In contrast, Lake Wolsey spring-time P levels represented the minimum observed during the ice-free season with averaged spring P concentrations generally at or below the interim PWQO of $10 \mu\text{g l}^{-1}$ and hence in the oligotrophic range (Error: Reference source not found⁶, Error: Reference source not found, Error: Reference source not found). Our results are consistent with Environment Canada's water quality assessment of Lake Wolsey in 2009 where lake-wide spring P concentrations were found to be generally at or below $10 \mu\text{g l}^{-1}$.

Table 4 Seasonal phosphorus concentrations ($\mu\text{g L}^{-1}$) for stations sampled by the Ontario Ministry of Environment (MOECC; 1986-2011), Environment Canada (EC; 2009) and Blue Goose /MTM Aquaculture (1998-2014)

Source	Season	N	Total Phosphorus ($\mu\text{g L}^{-1}$)					
			Median	Arithmetic Mean	Minimum	Maximum	Standard Error	Standard Deviation
MOECC (1986 - 1999)	Spring	28	8.0	9.7	6	18.0	0.65	3.44
	Summer	8	11.0	11.8	8	18.0	1.39	3.92
	Fall	27	16.0	13.8	3	24.0	1.39	7.24
MOECC (2008 - 2014)	Spring	23	6.9	7.3	4.4	10.8	0.39	1.88
	Summer	30	11.8	10.1	5.5	17.0	0.61	3.32
	Fall	32	13.9	14.2	11	19.8	0.43	2.42
Blue Goose / MTM Aquaculture (1998 - 2004)	Spring	63	8.0	8.8	4.0	30.0	0.41	3.27
	Summer	93	10.0	10.6	4.0	21.0	0.29	2.80
	Fall	104	10.0	10.5	5.0	19.0	0.27	2.76
Blue Goose / MTM Aquaculture (2004 - 2014)	Spring	152	10.9	12.6	1.0	64.1	0.84	10.41
	Summer	181	12.0	14.0	1.0	43.6	0.67	8.99
	Fall	242	15.0	16.8	1.6	150.0	0.84	13.01
	Winter	6	4.9	4.9	3.7	6.4	0.38	0.94
EC	Spring	11	9.0	9.1	6.1	12.4	0.52	1.71

* Environment Canada (EC) spring (May 05/09) phosphorus data from NAR (2010)

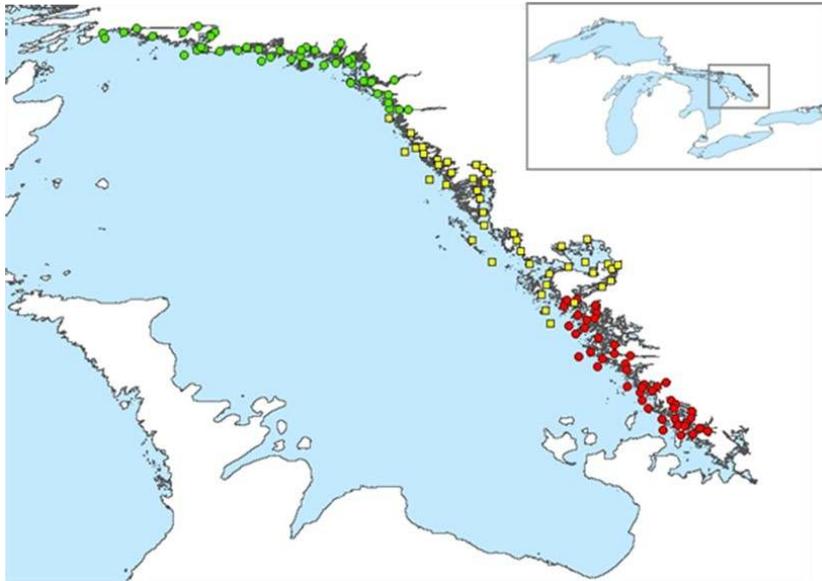


Figure 8 Spatial map of all the MOECC stations (135) sampled for the Georgian Bay Water Quality Study in 2003 (●), 2004 (■) and 2005 (●) (from Diep et al, 2007)

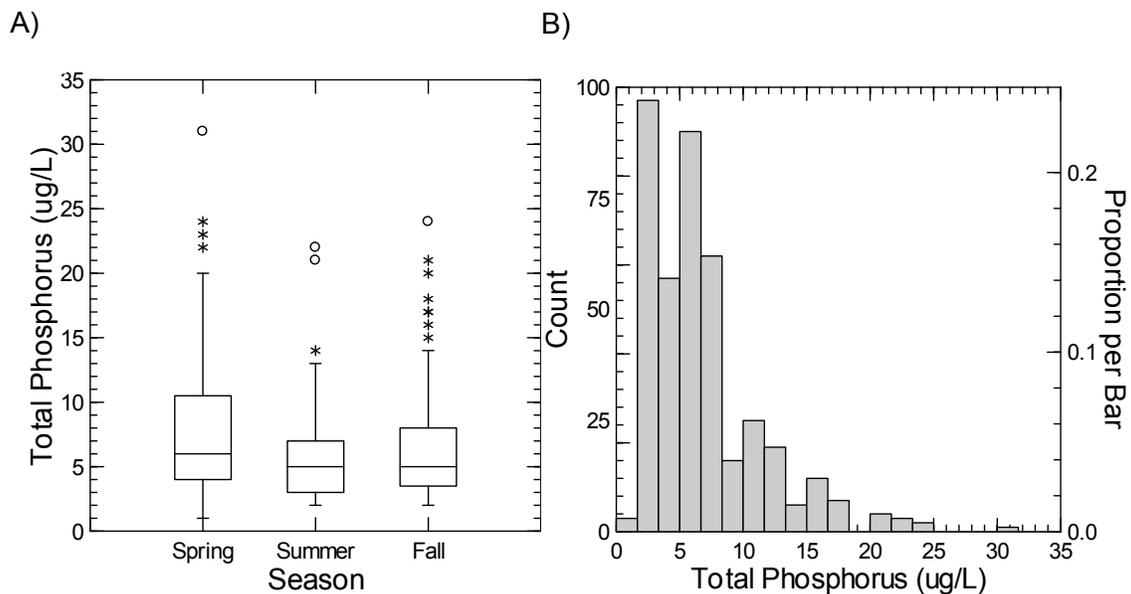


Figure 5 Georgian Bay Total phosphorus 2003-2005 (A) seasonal concentrations; and (B) frequency distribution curves (N = 405; data from Diep et al, 2007)

When we partitioned the data by season, we found spring P levels were significantly lower than summer and fall (ANOVA, $p < 0.01$), with P levels up to 2-fold higher compared to the spring and exceeded the interim PWQO of $10 \mu\text{g l}^{-1}$ (Error: Reference source not found, Error: Reference source not found). This phosphorus trend was consistent between years and with previous observations of elevated fall P concentrations (Hamblin and Gale, 2002). When

plotted against Julian day, this P pattern is clearly exhibited (Figure 9) in the recent MOECC (2008 – 2011) dataset for the April – September period. This seasonal pattern is consistent with modelled and measured monthly P concentrations for Lake Wolsey in 2007 from Milne et al (2015). However, Blue Goose/MTM Aquaculture data from the 1998 – 2004 period exhibited a modified trend of increasing P concentrations confined to the May to July period (Figure 10).

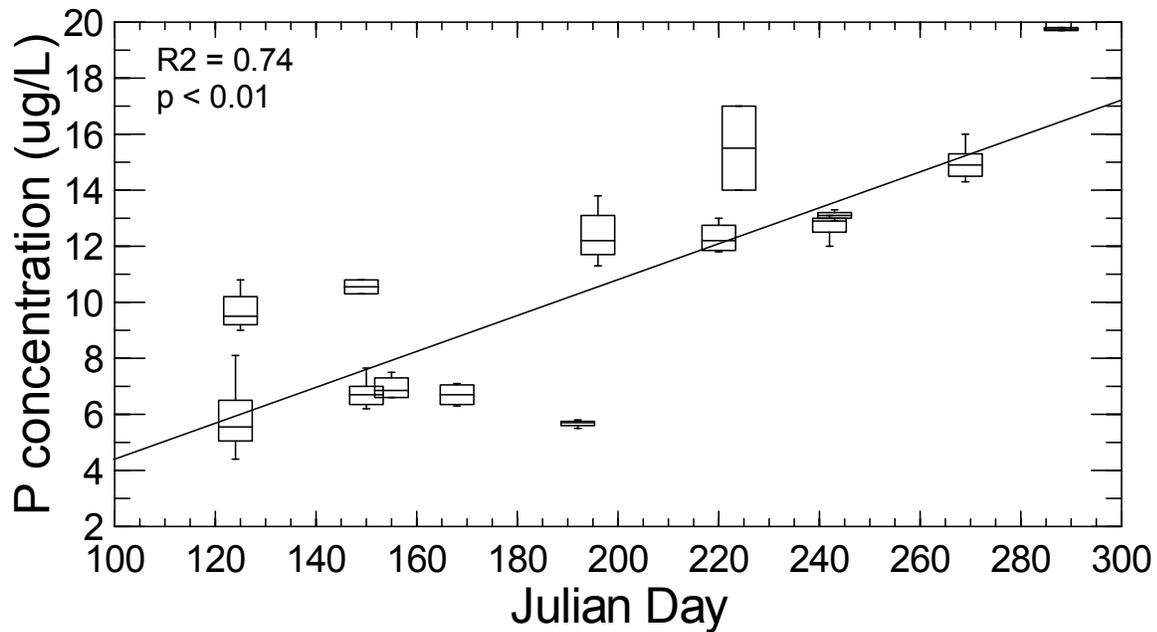


Figure 9 Total phosphorus concentrations ($\mu\text{g L}^{-1}$) as a function of Julian day over the ice-free season from April to October, Lake Wolsey (MOECC data, 2008 - 2011)

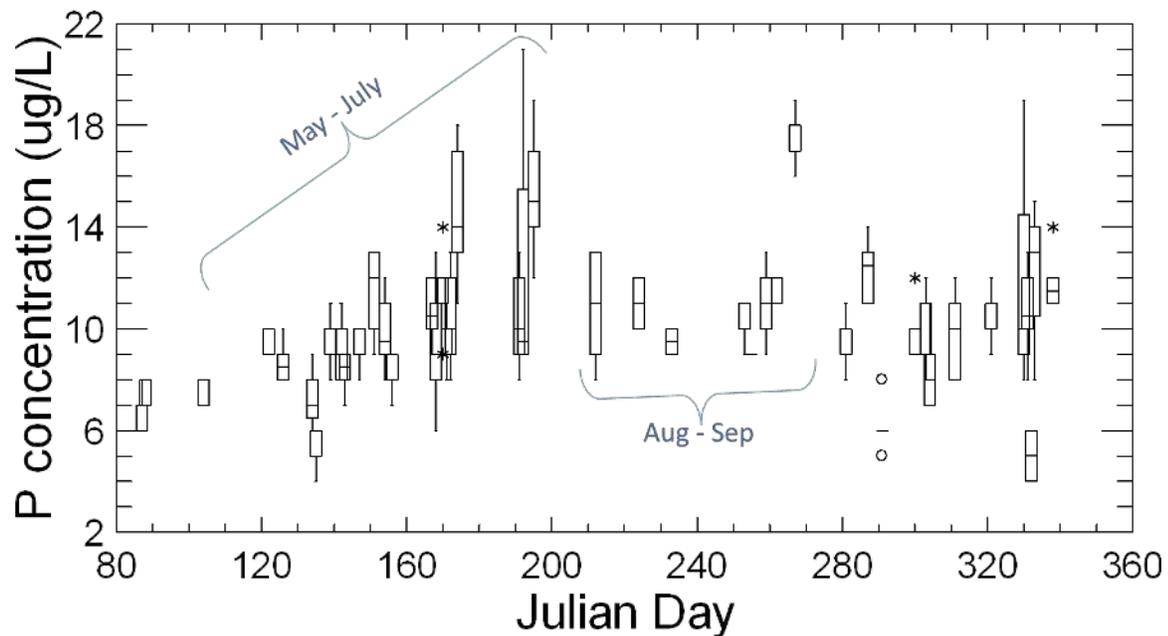


Figure 10 Total phosphorus concentrations ($\mu\text{g L}^{-1}$) as a function of Julian day over the ice-free season, Lake Wolsey (Blue Goose/MTM Aquaculture, 1998 - 2004)

When the bottom-waters are well-oxygenated, typically in early summer and when the water column is mixed, hypolimnetic P concentrations are generally below the PWQO of $10 \mu\text{g/L}$. For example, in early summer 2009, hypolimnetic P concentrations ranged from 7 to $9 \mu\text{g l}^{-1}$ and were even lower than the epilimnetic concentrations of 12 to $14 \mu\text{g l}^{-1}$ (Error: Reference source not found, Table 5). For sensitive systems, progression of the stratified season and continued depletion of the available oxygen in the hypolimnion can lead to functional anoxia, DO concentrations below 1 or 2 mg/L , resulting in elevated P levels in the hypolimnion as conditions became reduced and P is released from the sediment and back to the water column (Nurnberg, 1996). We find internal P loading effects do occur in this embayment, primarily in late-summer when the hypolimnion is severely DO depleted.

In 2013, samples taken from three depths were found to exhibit a vertical gradient of increasing P concentration with depth (). P concentrations from the bottom waters (24 m) were two-fold higher compared to the upper mixed layer (5 m) (). Internal P loading was observed in recent years and occurred basin-wide at stratified sites in late-summer with hypolimnetic P concentrations ranging from 17 to $57 \mu\text{g l}^{-1}$ and were up to 6-fold higher (Error: Reference source not found, Error: Reference source not found, Table 5). This is consistent with observations by Milne et al (2015) and in their phosphorus mass balance study, where they concluded that though internal P loading occurs in this embayment it was a minor component of the total P load to the system.

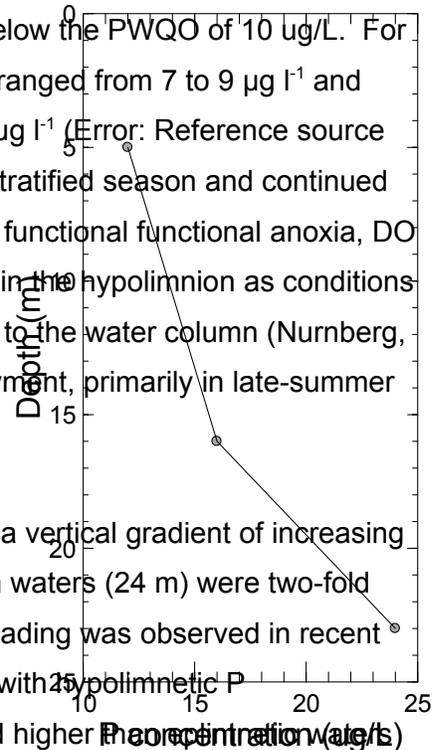


Figure 11 Total phosphorus concentrations ($\mu\text{g L}^{-1}$) with depth, Lake Wolsey (August 28, 2013)

Phosphate concentrations in the surface waters of Lake Wolsey were generally at or below trace levels, except at the deep site (Stn 595) in October 2008 where fall phosphate levels reached $\sim 12 \mu\text{g l}^{-1}$ and total P concentrations reached $\sim 20 \mu\text{g l}^{-1}$ (Error: Reference source not found, Error: Reference source not found). Hypolimnetic phosphate concentrations are typically at detectable levels in late-summer and were elevated at the deeper stations with levels as high as $38 \mu\text{g l}^{-1}$, corresponding to elevated total P concentration in the hypolimnion (Table 5).

Table 5 Summary of hypolimnetic nutrient concentrations for sites samples in Lake Wolsey between 2008–2011

Survey Date	Station	Water Depth (m)	Total Phosphorus	Total Phosphorus	Phosphate	Total Kjeldahl Nitrogen	Nitrite	Nitrate	Total Ammonium
			(Dorset; $\mu\text{g L}^{-1}$)	(LaSB; $\mu\text{g L}^{-1}$)					
12-Aug-08	596	18.1	29.3	33.0	0.0178	0.310	0.008	0.061	0.0020 ^w
	595	22.5	57.2	48.0	0.0319	0.340	0.016	0.074	0.0310
15-Oct-08	595	22.5	23.8	21.0	0.0128	0.290	0.002 ^w	0.005 ^w	0.0020 ^w
	596	18.8	20.4	18.0	0.0062 ^w	0.280	0.001 ^w	0.005 ^w	0.0020
16-Jul-09	596	19.4	7.4	6.0 ^T	0.0007 ^T	0.220	0.004 ^T	0.020 ^T	0.0280
	595	23.2	8.1	7.0 ^T	0.0014 ^w	0.250	0.006 ^w	0.034 ^w	0.0340
	236	22.9	8.1	6.0 ^T	0.0011 ^T	0.220	0.005	0.034 ^T	0.0300
	237	20.2	7.8	6.0	0.0011 ^T	0.230	0.005	0.025 ^T	0.0300
	238	15.1	9.3	9.0 ^T	0.0009 ^T	0.240	0.001 ^w	0.010 ^w	0.0280
	596	18.4	44.9	38.0	0.0326	0.220	0.004 ^T	0.094	0.0370
31-Aug-10	595	23.2	55.6	50.0	0.0382	0.270	0.008	0.098	0.0670
	236	22.7	38.4	32.0	0.0326	0.210	0.007	0.134	0.0430
	235	12.7	13.8	8.0 ^T	0.0058	0.230	0.002 ^T	0.021 ^T	0.0350
	229	17.3	27.4	23.0	0.0158	0.230	0.003 ^T	0.049 ^T	0.0330
	237	19.8	20.3	14.0	0.0105	0.190	0.001 ^w	0.092	0.0230
	238	15.0	14.3	9.0 ^T	0.0047	0.220	0.001 ^w	0.041 ^T	0.0120
09-Aug-11	598	19.1	25.1	18.0	0.0141 ^w	0.200	0.001 ^w	0.082 ^w	0.0160
	229	16.8	22.5	18.0	0.0122	0.240	0.008	0.047	0.0540
	595	23.5	55.2	45.0	0.0350	0.310	0.027	0.087	0.1060
	596	18.2	17.1	14.0	0.0084	0.230	0.014	0.052	0.0480
	598	22.4	42.4	33.0	0.0268	0.290	0.024	0.080	0.0990

^T A measurable trace amount

^w Below the method detection limit

Based on these results we conclude that Lake Wolsey is a mesotrophic system with minimum P concentrations observed in the spring, before summer stratification, and ice-free average P concentrations above the PWQO of 10 $\mu\text{g/L}$. Internal loading occurs in this system with elevated P concentrations in the bottom-waters of this embayment in late-summer. The elevated P in the summer and fall suggests additional, non-watershed based inputs of nutrients to the Lake Wolsey and the elevated hypolimnetic P concentrations in late-summer indicate that internal P loading is occurring driven by anoxia in the bottom-waters of Lake Wolsey.

3.1.2 Nitrogen

Nitrogen, an essential nutrient for phytoplankton, is an abundant non-limiting nutrient in temperate freshwater systems. In Lake Wolsey, total kjeldahl nitrogen (TKN) concentrations were generally low ranging from 0.20 mg l^{-1} to 0.35 mg l^{-1} , with maximum TKN concentration observed at the near-cage site (Stn 596). Annual-averaged nitrogen levels were slightly higher

in 2008 with 0.31 mg l^{-1} TKN compared with 0.24 to 0.25 mg l^{-1} observed between 2009 and 2011. TKN levels were relatively homogeneous throughout the embayment (Error: Reference source not found, Error: Reference source not found).

Nitrite concentrations were low and either below the method detection limit or at trace levels for all stations and across years (Error: Reference source not found, Error: Reference source not found). Nitrate levels were also low and below detection in 2008 and 2009, however detectable levels of nitrate were observed with concentrations reaching 0.36 mg l^{-1} in the spring of 2010. Total ammonium concentrations ranged from below the method detection limit (0.002 mg l^{-1}) to 0.041 mg l^{-1} (Error: Reference source not found, Error: Reference source not found).

There were slight differences between surface water and bottom-water nitrogen levels. For TKN, hypolimnetic concentrations were slightly lower than in the epilimnion. Hypolimnetic TKN values ranging from 0.19 mg l^{-1} to 0.34 mg l^{-1} , with maximum concentrations observed at the deep site (Stn 595) (Table 5). Hypolimnetic nitrite concentrations were also low and ranged from non-detect (0.001 mg l^{-1}) to 0.016 mg l^{-1} . As would be expected, nitrate levels were typically higher than nitrite, with hypolimnetic nitrate concentrations ranging from non-detect (0.005 mg l^{-1}) to 0.134 mg l^{-1} with maximum concentration observed at the deep sites (Table 5).

Bottom-water total ammonium concentrations varied widely and exceeded concentrations observed in the surface waters. Total ammonium concentrations ranged from below the detection limit (0.002 mg l^{-1}) to 0.067 mg l^{-1} with maximum concentrations observed in the hypolimnion at the deep sites in 2010. In 2008 (Table 5), bottom-water total ammonium concentrations were lower than levels observed in the surface waters with the largest difference observed at the near-cage site in the spring where the surface water total ammonium concentration was 0.0125 mg l^{-1} and bottom water concentration was 0.006 mg l^{-1} .

3.2 Chlorophyll a

Phytoplankton are primary producers at the base of the aquatic food web. Chlorophyll a is frequently used as an indicator of the phytoplankton standing crop conditions of a water body to infer productivity. Two approaches were used to characterize the chlorophyll a patterns in Lake Wolsey including water quality monitoring samples and through the use of real-time continuous in situ chlorophyll a sensors. The chlorophyll a sensors were deployed in the surface waters (5

m below water surface) of Lake Wolsey at both the deep proximal site (Stn 595) and near-cage site (Stn 596) during the ice-free season in 2008 and 2010 and chlorophyll a was measured by fluorescence light scattering. Field-based water quality monitoring provided us with empirical measures of chlorophyll a concentration. Combined these data provide us with a better understanding of phytoplankton dynamics in this embayment.

We found Lake Wolsey to be a moderately productive system with chlorophyll a concentrations ranging from 1.1 $\mu\text{g l}^{-1}$ to 4.7 $\mu\text{g l}^{-1}$ (Error: Reference source not found, Error: Reference source not found). Inter-annual variability was evident over the period 2008 to 2011. Similar seasonal patterns were observed in 2009 and 2010 with low spring chlorophyll a concentrations ($< 2 \mu\text{g l}^{-1}$) increasing to 3.4 – 4.6 $\mu\text{g l}^{-1}$ in the summer and fall (Error: Reference source not found, Error: Reference source not found). This seasonal trend was not observed in 2008 and 2011 when chlorophyll concentrations generally remained above 3 $\mu\text{g l}^{-1}$ throughout the ice-free season (Error: Reference source not found, Error: Reference source not found). Chlorophyll a levels were relatively homogeneous lake-wide, however Stations 237, 238 and 598 located near the culvert that connects Lake Wolsey to the North Channel generally exhibited slightly lower chlorophyll a concentrations compared to the southwest and southern stations.

Real-time in situ measures of fluorescence provided us with high resolution data to ascertain temporal patterns in chlorophyll a during the ice-free season. Although chlorophyll a patterns were variable between stations and years, we observed fluorescence peaks in Jun/July with secondary smaller peaks in September/October in both years and across stations (Figure 12). Primary productivity is expected to be highest when water temperature and light availability is high and this typically corresponds with the mid to late-summer time period (e.g., August). However, both daily-averaged and monthly-averaged chlorophyll a, clearly show elevated fluorescence in mid-summer (July) and after fall turnover (September/October). Lake Wolsey is not a light-limited system, as indicated by the low DOC levels and high secchi depths (, Table 8). The occurrence of the fluorescence peaks in June/July highlights the possibility that these peaks may be indicative of the formation of algal blooms, while the fall fluorescence peaks may be indicative of fall turnover events or algal blooms as a result of increasing P levels in the surface waters (Error: Reference source not found, Error: Reference source not found).

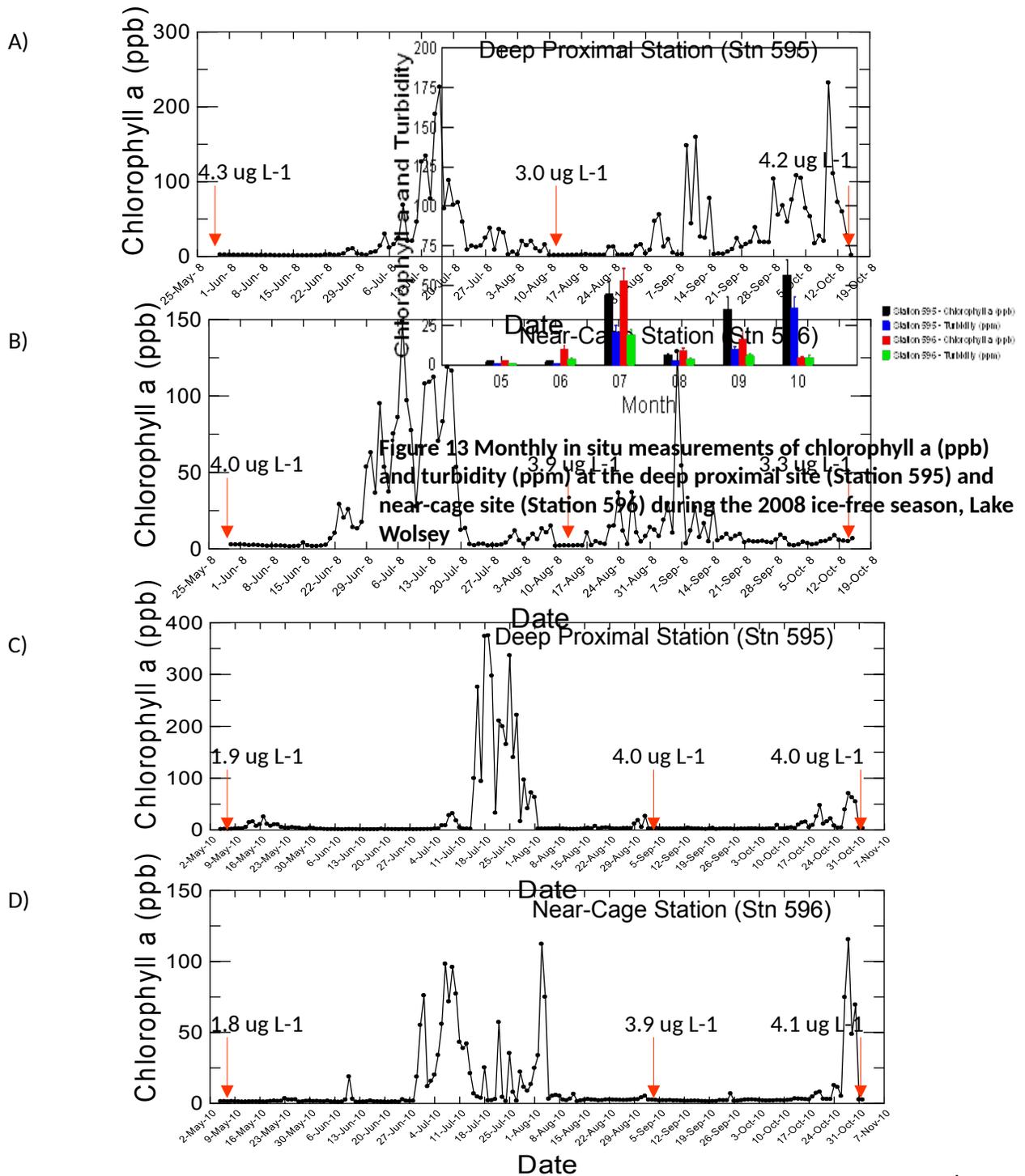


Figure 12 Real-time continuous daily-averaged chlorophyll a (ppb) concentration through the ice-free season at 5 m below the water surface at A) Station 595 (2008) B) Station 596 (2008) C) Station 595 (2010) and D) Station 596 (2010). Arrows (→) indicate extracted samples taken by MOECC.

In 2008 monthly-averaged chlorophyll a levels were highest in July (Figure 13). Elevated levels were also observed in September and October at the deep proximal station (Stn 595). In 2008,

chlorophyll a varied from 1.0 to 231.8 ppb and 1.4 to 149.7 ppb at the deep proximal site (Stn 595) and near-cage site (Stn 596). Annual-averaged chlorophyll a levels for Stns 595 and 596 were 28.0 ppb and 19.6 ppb, respectively, in 2008.

In 2010, we observed the same seasonal pattern with maximum chlorophyll a values in July at the deep station (Stn 595) ranging from 0.9 to 195.6 ppb. Chlorophyll a values were comparatively lower at the near-cage station (Stn 596) with values ranging from 0.9 to 113.9 ppb, and this may be due to high dreissenid colonization at the cage aquaculture operation due to biofouling. The higher chlorophyll a values observed at the deep station suggests higher productivity at the deep proximal site. Near the culvert (Stn 598), fluorescence peaks also exhibited a similar seasonal pattern.

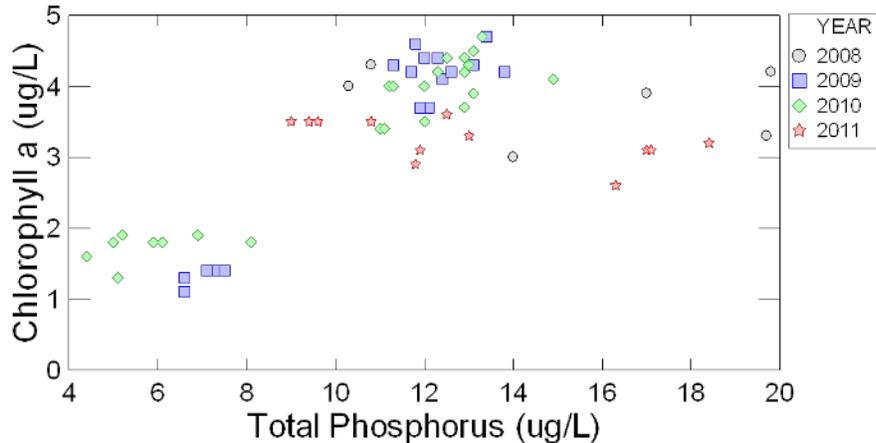


Figure 14 Relationship between total phosphorus ($\mu\text{g L}^{-1}$) and chlorophyll a concentration ($\mu\text{g L}^{-1}$), Lake Wolsey, 2008–2010

Plotting chlorophyll a concentration against total P concentration by year demonstrated a significant positive relationship between chlorophyll a and P in 2009 and 2010 (Figure 14), with P explaining $\sim 88\%$ of the variability in chlorophyll a concentrations. No statistically significant relationship was observed in 2008 and 2011. Although P concentrations increased over the 2008 and 2011 ice-free season, chlorophyll a levels remained below $5 \mu\text{g l}^{-1}$ across stations and seasons even when P levels approached $20 \mu\text{g l}^{-1}$.

To determine if the particulate pool is driven by the amount of phytoplankton in the water column, the relationship between daily-averaged chlorophyll a and turbidity was first examined. We found turbidity to be significantly correlated with chlorophyll a levels at Stn 595 for both years, with chlorophyll a explaining $> 75\%$ of the variability in turbidity (Error: Reference source

not found). At the near-cage site, the correlation was weaker with chlorophyll a explaining only 68% and 32% of the variability in 2008 and 2010, respectively, potentially due to the solid waste loading from the cage aquaculture operation which has the potential to increase the particulate pool in the immediate vicinity of the cage aquaculture operation.

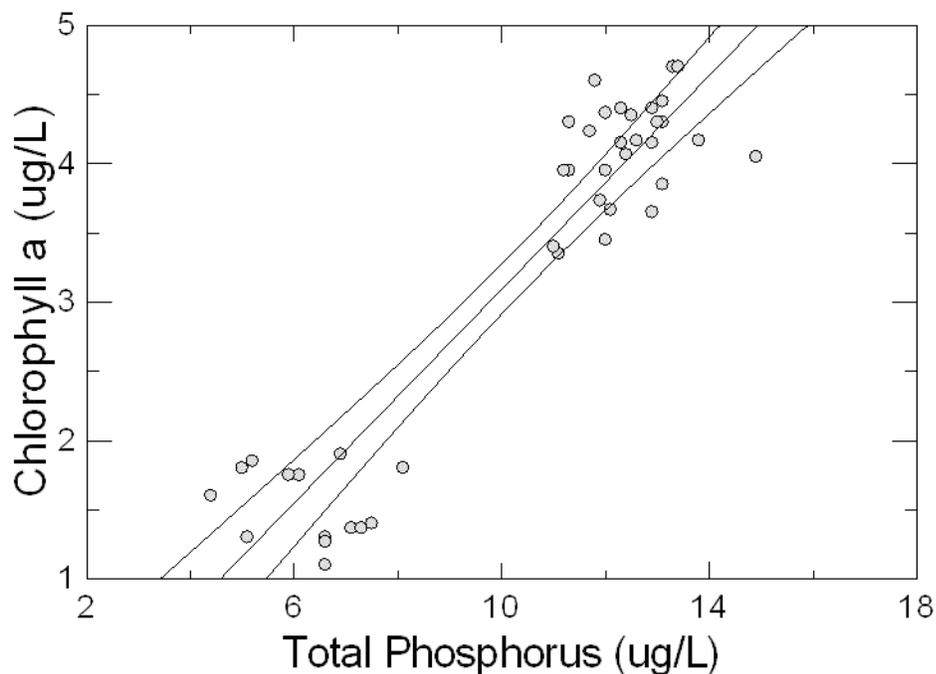


Figure 15 Relationship between total phosphorus ($\mu\text{g L}^{-1}$) and chlorophyll a concentration ($\mu\text{g L}^{-1}$), Lake Wolsey, 2009 and 2010.

In general, the correlation between turbidity and chlorophyll was higher in 2008 compared to 2010. Near the culvert (Stn 598) there was a significant and strong relationship between turbidity and chlorophyll a with chlorophyll a explaining $\sim 81\%$ of the variability in turbidity, which suggests phytoplankton standing crop is contributing more particles to the suspended solids pool.

We used our data from our water quality surveys to ground-truth these measurements. Although we found good correspondence between the two datasets with chlorophyll a

concentrations ranging from $1.8 \mu\text{g L}^{-1}$ to $4.2 \mu\text{g L}^{-1}$ corresponding to chlorophyll a fluorescence of $< 5 \text{ ppb}$, our water sampling surveys did not coincide with the timing of the fluorescence peaks ($> 100 \text{ ppb}$) (Figure 12).

These real-time continuous *in situ* sensors provided us insight on both the spatial and temporal patterns in phytoplankton standing stock. Chlorophyll a patterns indicate a highly dynamic system with periodic chlorophyll a peaks in mid-summer and early fall that occur annually. Spatial patterns were distinct with potentially higher productivity at the deep station (Strn 595) and near the culver, as indicated by high chlorophyll a fluorescence.

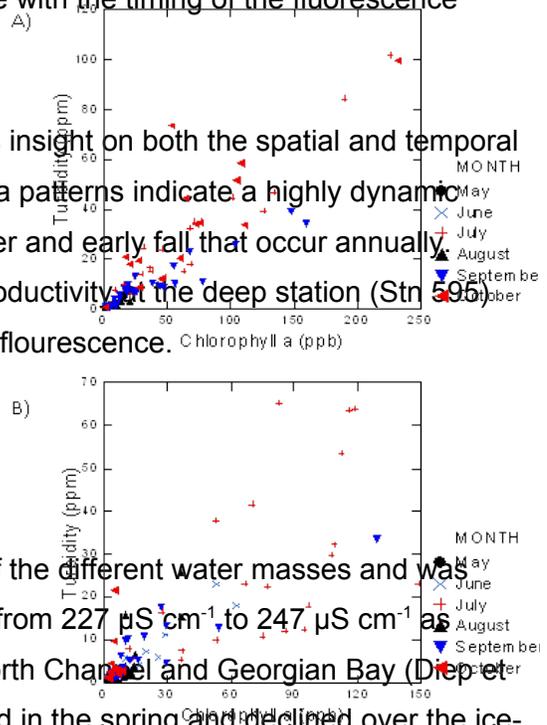


Figure 16 The relationship between turbidity (ppm) and chlorophyll a (ppb) for A) Station 595 (deep site) and B) Station 526 (near culvert) during the 2008 ice-free season, Lake Wolseley.

3.3 Water Chemistry

3.3.1 Conductivity, Alkalinity and Chloride

Conductivity measurements can be used as a tracer of the different water masses and was observed to be relatively high in Lake Wolseley ranging from $227 \mu\text{S cm}^{-1}$ to $247 \mu\text{S cm}^{-1}$ as compared with $\sim 180 \mu\text{S cm}^{-1}$ for the open waters of North Channel and Georgian Bay (Diehl et al, 2007). Maximum conductivity values were observed in the spring and declined over the ice-free season. This suggests a higher lake influence on the water quality of Lake Wolseley in the summer and fall. Conditions were similar between stations; however there were slight inter-annual differences. On average, conductivity values in 2010 were slightly lower than those observed in 2008 or 2009, suggesting a higher lake influence on water quality in 2010.

Hypolimnetic conductivity values were slightly higher compared to the epilimnion and ranged from $233 \mu\text{S cm}^{-1}$ to $249 \mu\text{S cm}^{-1}$ and this difference was most notable in 2010 and 2011 (Table 6).

Lake Wolseley is an alkaline waterbody with alkalinity levels ranging from 90 mg l^{-1} to 103 mg l^{-1} (Table 6, Table 7). As expected, hardness and calcium levels are high ranging from 107 mg l^{-1} to 124 mg l^{-1} and 27 mg l^{-1} to 31 mg l^{-1} , respectively. This hard-water system is spatially homogenous with low between-station variability, however seasonal patterns were evident. Alkalinity was highest in the spring and declined over the ice-free season, except in 2011 where lower summer alkalinity levels were followed by a slight increase in the fall (, Table 8). Inter-annual differences were also observed with 2010 having slightly lower values . Hypolimnetic conditions were similar to epilimnetic conditions in 2008 and 2009, however in 2010 the hypolimnion was more alkaline than the epilimnion (Table 8).

pH levels in this embayment were more variable than alkalinity with pH ranging from 8.08 to 8.39 (Table 6, Table 7). Lake Wolsey exhibited seasonal and interannual differences in pH with maximum pH observed in the summer, except in 2009, which suggests potentially higher watershed/anthropogenic inputs to the embayment during the summer stratified season.

Chloride, a conservative ion used typically as an indicator of anthropogenic influence, is present in low quantities in Lake Wolsey. Lake Wolsey chloride levels exhibit low variability with concentrations ranged from 4.8 mg l⁻¹ to 5.6 mg l⁻¹ (, Table 8). Conditions are homogeneous and between-station variability was low. Although seasonal differences were not observed, slight interannual variability was noted. Chloride levels were slightly lower in 2009, which suggests lower anthropogenic or allochthonous influence on the water quality of this embayment. Hypolimnetic chloride concentrations are consistent with levels observed in the epilimnion, except for the mid-lake site (Stn 237) where the concentration reached 6.6 mg l⁻¹ (Table 6).

3.3.2 Conductivity

Conductivity, which provides us with an indication of the amount of ions in the water, is a good tracer of the mixing between two water masses if these water masses are biogeochemically distinct from each other. In 2010, we deployed real-time continuous conductivity sensors in the surface waters (~ 5 m) at three locations in Lake Wolsey, Stns 595, 596 and 598 to determine both spatial and temporal (within-year) variability in conductivity conditions. The data presented here is temperature corrected (25°C) and has been hourly and daily averaged to facilitate comparisons.

At the deep proximal site (Stn 595), conductivity values ranged from 226 $\mu\text{S cm}^{-1}$ to 242 $\mu\text{S cm}^{-1}$ with an annual averaged conductivity level of 233 $\mu\text{S cm}^{-1}$. The range in conductivity was smaller at the near-cage site (Stn 596) with values ranging from 227 $\mu\text{S cm}^{-1}$ to 240 $\mu\text{S cm}^{-1}$, however annual averaged conductivity was similar. At a site ~ 1 km away (Stn 598), conductivity values varied more broadly, ranging from 224 $\mu\text{S cm}^{-1}$ to 249 $\mu\text{S cm}^{-1}$, however annual averaged conductivity was the similar. The large range in conductivity values may be due to the site's proximity to the causeway which connects Lake Wolsey to ionically-weaker waters of Campbell Bay/North Channel.

Temporal trends were similar between all stations with high conductivity values occurring in the spring and declined over the ice-free season (Figure 17). Sharp declines in conductivity, followed by rapid recovery, were observed in mid-June, mid-July and mid-August. The timing of these conductivity declines was consistent between stations (Figure 17) and suggests a lake-wide phenomenon. Declines in conductivity over the ice-free season indicate increasing lake influence on the water quality of Lake Wolsey and thus diminished watershed influence on this embayment

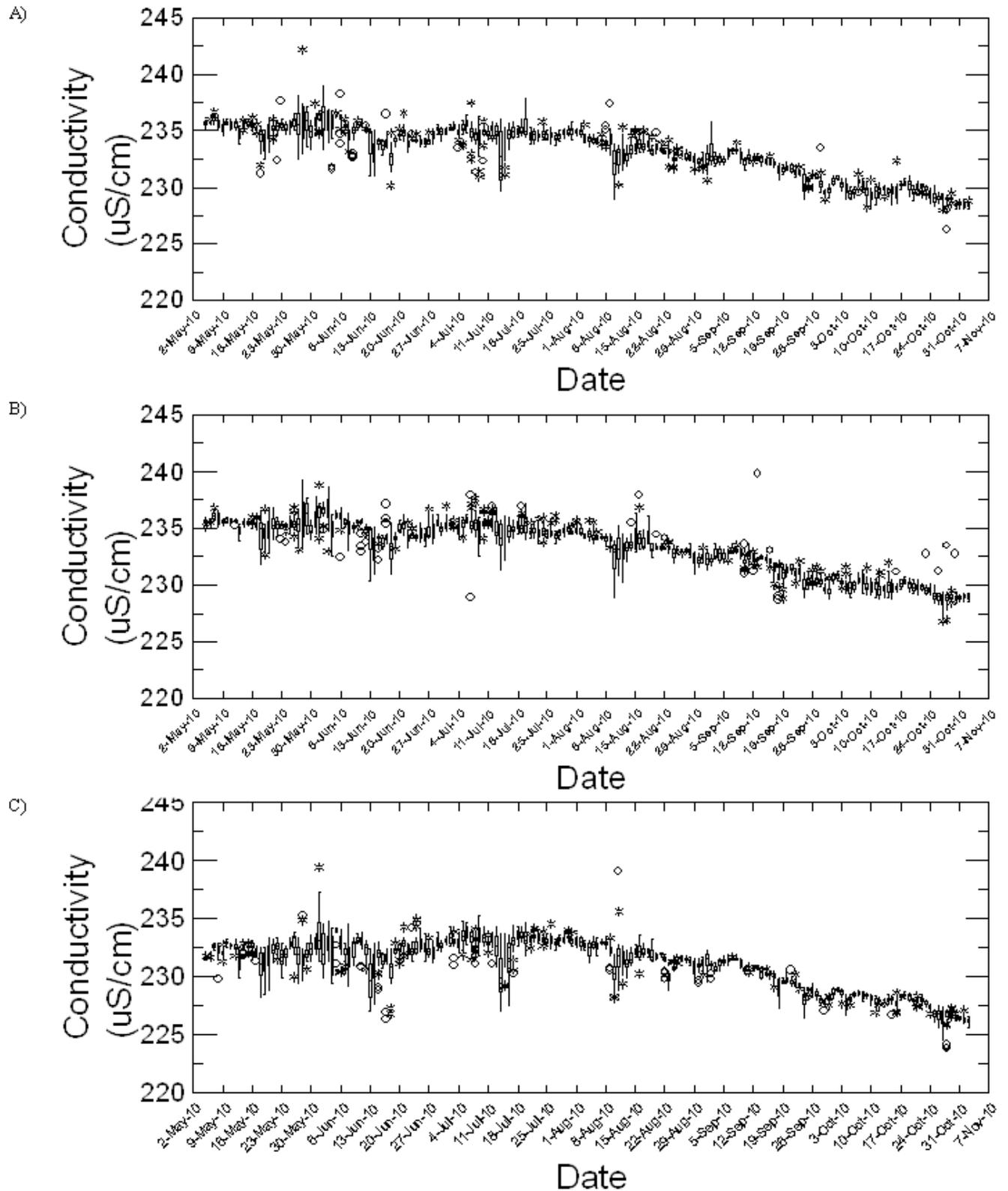


Figure 17 Hourly-averaged real-time continuous *in situ* conductivity ($\mu\text{S cm}^{-1}$) trends through the 2010 ice-free season at 5 m below the water surface at A) Station 595 B) Station 596 C) Station 598

3.3.3 Turbidity & Suspended Solids

Water clarity is a function of the amount of particles in the water column and elevated suspended solids concentrations can result in high turbidity and consequently low water clarity. We deployed real-time continuous *in situ* turbidity sensors were deployed in Lake Wolsey which provided us high resolution turbidity data, as measured infrared back-scattering, to track temporal patterns in this embayment.

Although water quality chemistry data indicates a system with low turbidity, the real-time sensors indicate a system with high variability both spatially and temporally in turbidity patterns. Turbidity was found to ranged from 0.4 ppm to 101.7 ppm and 0.5 ppm to 65.1 ppm at Stns 595 and 596, respectively, in 2008. These values greatly exceed the values (0.3 ppm to 73.1 ppm) observed in 2010, therefore 2008 conditions were generally more turbid comparatively. In 2008, turbidity peaks occurred in July with secondary peaks in late-summer/early fall, as indicated by the daily-averaged turbidity values against time plots (Figure 18). In 2010, turbidity peaks occurred between July and August at the deep station (Stn 595), while at the near-cage station (Stn 596) these peaks occurred in September with a smaller secondary peak in October.

There was good correspondence between the *in situ* chlorophyll *a* and turbidity data for the deep site (Stn 595), and to a lesser degree the near-cage site (Stn 596) (Error: Reference source not found), which indicate phytoplankton likely constitute a smaller proportion of the particulate pool at the near-cage site (Stn 596). Dreissenids are prevalent in Lake Wolsey, particularly in the vicinity of the cage aquaculture operation (Hille, 2008), and this potentially contributes to the lower particulate pool near the cage aquaculture operation by filtering and ingesting phytoplankton from the water column (e.g., Hecky *et al*, 2004), and potentially removing 8% - 67% of the algal biomass from the water column (Edwards *et al*, 2005).

In 2008 and 2010, we collected surface water samples and analyzed the samples for turbidity and suspended solids concentrations. These sampling events generally did not coincide with the turbidity peaks and we did not observe any turbidity or suspended solid values > 2 FTU or > 3 mg L⁻¹, respectively. We also collected bottom-water samples for turbidity and suspended solids concentration and we found the bottom-water samples to be more turbid and possessed higher suspended solids concentration than the surface waters (Table 6).

Based on the real-time continuous *in situ* information, we can conclude that water clarity was likely higher in 2010, as indicated by the lower turbidity values and this is supported by our field measurements of secchi depth where measured 2010 secchi depths exceeded 2008 conditions. The near-cage site is generally clearer than the deep proximal site comparison, possibly due to the presence of dreissenid mussels. From our water quality surveys we found turbidity and suspended solids concentrations to be moderately higher in the bottom waters compared to the surface waters of Stn 596, which suggest vertical gradients in particulate pool.

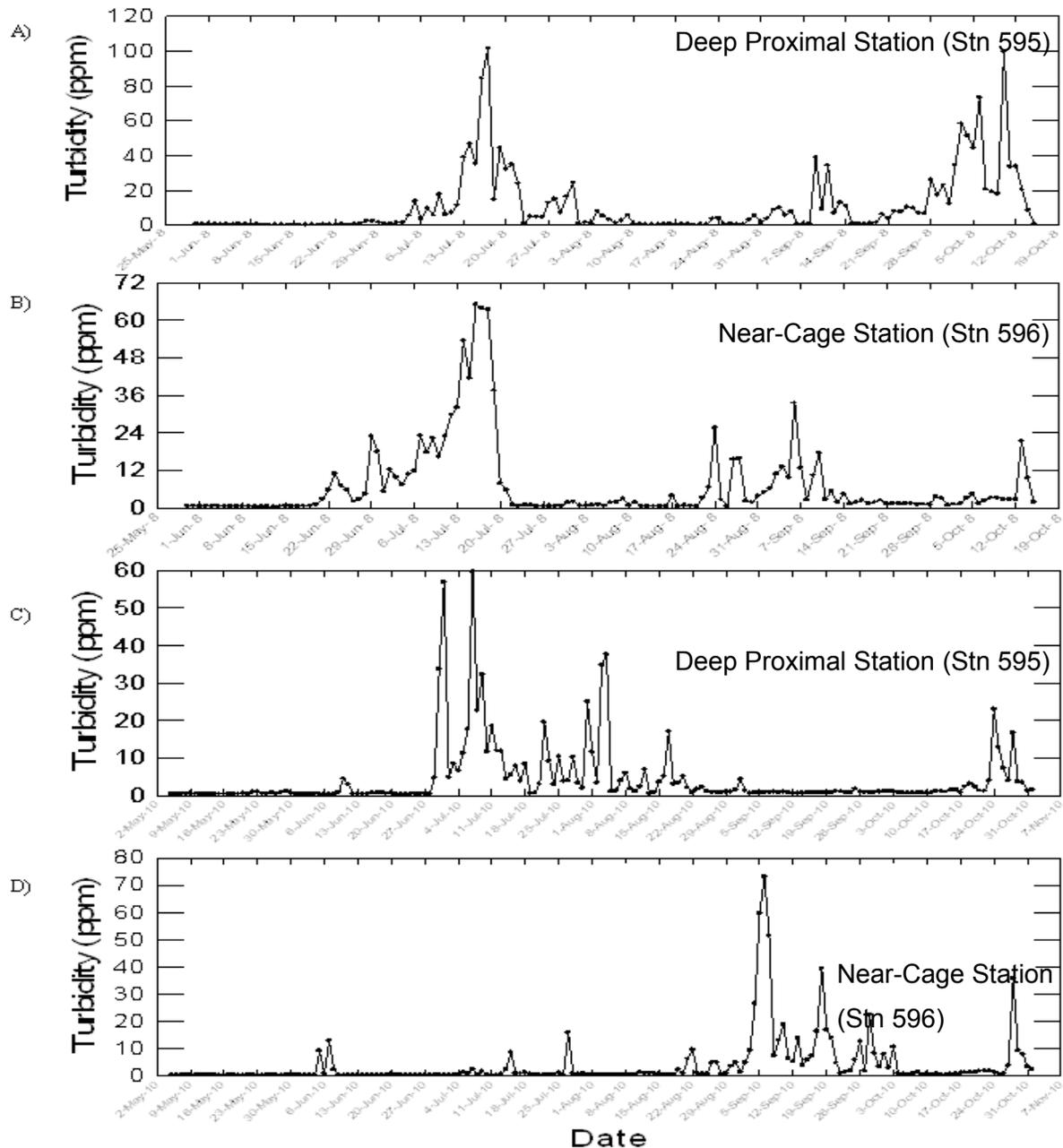


Figure 18 Daily-averaged real-time continuous *in situ* turbidity (ppm) trends through the ice-free season at 5 m below the water surface in 2008 at A) Station 595 B) Station 596 and in 2010 at C)

Station 595 D) Station 596

Table 6 Summary of hypolimnetic water chemistry data for sites samples in Lake Wolsey from 2008 to 2011

Survey	Station	Water Depth (m)	DIC (mg L ⁻¹)	DOC (mg L ⁻¹)	TSS (mg L ⁻¹)	Silicate (mg L ⁻¹)	pH	Chloride (mg L ⁻¹)	Conductivity (25°C) (µSiem cm ⁻¹)	Alkalinity (mg L ⁻¹)	Turbidity (FTU)
12-Aug-08	596	18.1	23.6	2.8	1.3 ^T	2.40	8.01	5.1	244	102.0	1.10
	595	22.5	25.3	2.4	2.8	3.02	8.03	5.1	245	103.0	1.19
16-Jul-09	596	19.2	23.6	2.8	0.7 ^T	1.12	8.08	4.9	245	99.6	0.64
	595	23.4	23.8	3.1	0.8 ^T	1.40	8.06	4.8	246	101.0	0.63
	236	22.8	23.7	2.8	1.0 ^T	1.36	8.05	4.9	247	102.0	0.80
	237	20.3	23.8	2.9	0.9 ^T	1.18	8.00	4.9	246	100.0	0.57
	238	15.0	23.5	3.0	1.1 ^T	0.80	8.13	4.9	243	99.9	0.72
	596	18.4	23.2	2.4	1.5 ^T	3.60	7.98	5.3	243	97.5	1.15
31-Aug-10	595	23.1	23.8	2.5	2.2 ^T	4.30	7.90	5.2	246	97.9	3.18
	236	22.7	23.9	2.6	1.6 ^T	4.12	7.92	5.2	244	98.0	2.08
	235	12.7	21.9	2.6	0.8 ^T	1.44	8.20	5.2	233	92.0	0.74
	229	17.2	22.9	2.5	0.8 ^T	2.96	7.99	5.2	242	96.8	0.90
	237	19.8	23.0	2.4	0.9 ^T	3.60	7.91	6.6	244	97.2	0.78
	238	15.0	21.5	2.6	0.8 ^T	1.52	8.19	5.2	233	91.5	0.68
	598	19.5	23.0	2.5	1.1 ^T	3.56	7.92	5.2	244	95.9	1.15
	229	16.8	25.3	2.9	1.1 ^T	2.76	8.26	5.8	245	95.8	0.56
9-Aug-11	595	23.5	24.8	2.8	1.5 ^T	3.46	8.25	5.3	249	99.3	1.46
	596	18.2	24.6	2.8	0.8 ^T	2.92	8.25	5.3	246	98.6	0.58
	598	22.4	25.2	2.9	0.8 ^T	3.28	8.26	5.7	249	99.6	0.81

Additional parameters that were measured include dissolved inorganic carbon (DIC) and silicate. Both DIC and silicate concentrations were low in this embayment with concentrations ranging from 21.1 mg l⁻¹ to 24.6 mg l⁻¹ and 0.5 to 1.8 mg l⁻¹, respectively (, Table 8). DIC concentrations were consistent between stations, season and years.

3.3.4 Dissolved Organic Carbon, Suspended Solids and Turbidity

In addition to nutrient status and measures of primary productivity, there are other water chemistry data that contribute to an understanding of the temporal and spatial water quality patterns of this embayment. Both suspended solids (SS) and dissolved organic carbon (DOC) represent sources of organic material for heterotrophs and are major determinants of water colour and clarity. Results show Lake Wolsey to be a relatively homogenous water body with low DOC (2.6 mg l⁻¹ to 4.1 mg l⁻¹) and low SS (0.5 mg l⁻¹ to 3.0 mg l⁻¹) (, Table 8), variability between stations and year is low. This embayment is a clear-water waterbody with average water colour of 4 total colour units (TCU) (2008 data only). DOC levels were generally at or

below 3 mg l^{-1} , except in 2010 when DOC concentration reached 4 mg l^{-1} at the south near-cage station (Stn 229) (). Comparison of Lake Wolsey DOC data to Prairie *et al* (2002) shows DOC levels to fall at the lower end of the DOC spectrum. Since clear-water water, low-DOC water bodies are generally not susceptible to natural DO depletion Prairie *et al* (2002), DOC is not expected to be the major contributor to the hypolimnetic DO depletion that has been observed in this embayment.

SS levels were generally at or below 2 mg l^{-1} , except in November 2009 and at the station near the culvert (Stn 598) in October 2011 (, Table 8). Although SS levels were generally at trace levels, in 2009 there was an increase SS over the ice-free season. In all years, maximum SS was observed in the fall, likely due to resuspension events during fall turnover. The low SS concentrations indicate a low particulate waterbody and this is supported by the turbidity data with from 0.4 FTU to 1.4 FTU, with maximum turbidity observed at the deep site (Stn 595) in the fall of 2008.

SS and DOC concentrations in hypolimnetic waters exhibited similar trends with DOC and SS levels at or below 3 mg L^{-1} . This suggests that the conditions that resulted in internal P loading effects in the late-summer season, did not affect SS and DOC levels in the bottom waters of this embayment. Turbidity levels were also generally below 2 FTU in the hypolimnion, except at the deep stations (Stn 595, 236) in 2010.

Secchi depth data were also recorded (minimum 1.8m, maximum 7.2m) and support the observation that this embayment is a generally a clear-water system. Secchi depths varied between years with high water clarity observed in 2009 (average 5.4 m) and moderate water clarity observed in 2011 (average 3.3m).

Table 7 Summary of epilimnetic water chemistry data for sites samples in Lake Wolsey from 2008 to 2010

Survey	Station	Water Depth (m)	DIC (mg L ⁻¹)	DOC (mg L ⁻¹)	TSS (mg L ⁻¹)	Silicate (mg L ⁻¹)	pH	Chloride (mg L ⁻¹)	Conductivity (25°C) (µSiem cm ⁻¹)	Alkalinity (mg L ⁻¹)	Turbidity (FTU)	Secchi (m)
2008												
29-May-08	596	19.0	22.3	2.7	1.6 ^T	0.7	8.19	5.0	244	100.3	0.84	4.8
	595	23.5	22.7	2.8	1.6 ^T	0.7	8.20	5.0	244	101.0	0.80	3.9
12-Aug-08	596	18.1	22.6	2.8	1.2 ^T	0.8	8.38	5.1	240	99.2	0.77	3.6
	595	22.5	22.9	3.1	1.0 ^T	0.8	8.39	5.1	238	99.9	0.62	3.9
15-Oct-08	595	22.5	24.6	2.8	1.7 ^T	0.5	8.23	5.4	234	97.2	1.35	4.6
	596	18.8	23.6	2.8	1.5 ^T	0.5	8.16	5.4	236	96.5	1.16	4.7
2009												
5-Jun-09	596	18.6	22.3	2.8	0.6 ^T	0.6	8.16	4.9	243	100.5	0.52	6.1
	595	22.8	22.7	2.9	0.7 ^T	0.6	8.22	4.9	242	100.5	0.53	5.9
	235	12.9	22.6	2.9	0.8 ^T	0.6	8.19	4.9	246	100.0	0.53	6.1
	236	22.6	22.5	3.0	0.5 ^W	0.6	8.24	4.9	248	103.0	0.45	5.3
	237	19.9	22.6	2.9	0.7 ^T	0.6	8.17	4.9	246	100.2	0.66	5.9
16-Jul-09	238	14.9	22.3	2.8	0.6 ^T	0.6	8.14	4.9	242	99.7	1.07	6.4
	596	19.4	23.1	2.9	1.4 ^T	0.5	8.20	4.9	243	100.0	0.83	5.9
	595	23.2	23.2	3.3	1.3 ^T	0.5	8.17	4.9	242	99.3	0.90	5.2
	236	22.9	23.0	3.1	1.4 ^T	0.5	8.18	4.9	244	99.0	0.78	4.8
	235	13.2	22.9	3.0	1.5 ^T	0.5	8.08	4.9	242	99.1	0.78	5.6
03-Nov-09	237	20.2	23.3	3.1	1.5 ^T	0.5	8.19	4.9	241	99.1	0.77	5.9
	238	15.1	23.0	3.1	1.4 ^T	0.5	8.22	4.9	244	99.1	0.87	5.0
	238	15.1	22.0	2.6	2.1 ^T	1.0	8.17	4.9	233	94.5	0.97	5.2
	237	9.5	22.0	2.6	2.2 ^T	1.0	8.16	4.9	231	94.6	0.77	5.0
	235	12.9	22.0	2.7	2.9	1.0	8.18	4.8	233	95.3	1.12	4.4
2010	236	23.0	21.9	2.7	3.0	1.0	8.17	4.8	234	94.5	1.07	4.9
	595	23.0	22.2	2.7	2.5	1.0	8.18	4.8	231	94.4	1.05	5.0
	596	19.2	22.8	2.7	2.6	1.0	8.20	4.9	230	94.4	1.1	4.8
05-May-10	595	22.7	22.5	2.8	1.1 ^T	1.0	8.25	5.1	232	95.8	0.48	6.0
	596	18.9	22.4	2.7	0.9 ^T	1.0	8.31	5.1	237	98.2	0.48	6.1
	229	16.9	22.3	2.8	0.9 ^T	1.0	8.31	5.1	236	97.1	0.55	5.5
	235	13.0	22.3	2.8	0.6 ^T	1.0	8.31	5.1	236	98.2	0.49	5.5
	236	22.7	22.4	2.7	0.8 ^T	1.0	8.32	5.2	237	97.6	0.42	5.2
	598	19.9	22.6	2.8	1.0 ^T	1.0	8.31	5.2	236	98.4	0.43	7.2
	237	20.0	22.4	2.7	0.9 ^T	1.0	8.31	5.2	234	97.9	0.56	6.5
	238	15.0	22.2	2.7	1.2 ^T	1.0	8.29	5.2	236	97.5	0.46	5.8
31-Aug-10	596	18.4	21.5	2.7	0.7 ^T	1.2	8.23	5.4	234	92.2	0.95	4.0
	595	23.2	21.2	2.6	1.0 ^T	1.1	8.39	5.3	232	92.0	0.89	4.5
	236	22.7	21.4	2.7	0.8 ^T	1.1	8.36	5.2	234	92.2	0.87	4.1
	235	12.7	21.4	2.7	0.8 ^T	1.1	8.32	5.2	232	92.0	0.64	4.0
	229	17.3	21.2	2.6	0.6 ^T	1.1	8.31	5.2	232	91.7	0.66	4.5
01-Sep-10	237	19.8	21.1	2.7	0.8 ^T	1.1	8.35	5.3	232	92.0	1.03	3.5
	238	15.0	21.4	2.7	0.8 ^T	1.1	8.39	5.2	231	91.6	1.01	3.8
	598	19.1	21.3	2.6	0.9 ^T	1.2	8.32	5.3	233	92.2	0.74	3.8
02-Nov-10	598	21.5	22.9	3.1	1.7 ^T	1.8	8.21	5.2	228	90.0	0.89	5.0
	235	12.5	22.7	2.8	1.9 ^T	1.8	8.19	5.6	228	90.6	1.32	4.1
	229	16.5	22.7	4.1	1.7 ^T	1.8	8.22	5.3	227	93.4	0.96	4.6
	596	18.4	23.1	3.0	1.5 ^T	1.8	8.23	5.3	228	90.2	0.83	5.5
	595	22.8	23.0	2.9	1.4 ^T	1.8	8.22	5.2	228	90.8	0.97	5.6
	236	22.4	23.0	2.9	1.2 ^T	1.8	8.23	5.2	230	90.4	0.96	5.0
	237	19.7	22.9	2.9	1.3 ^T	1.8	8.22	5.2	228	90.5	0.85	4.7
238	15.0	22.9	2.8	1.1 ^T	1.8	8.24	5.1	229	90.4	0.95	4.5	

T A measurable trace amount

W Below the method detection limit

Table 8 Summary of epilimnetic water chemistry data for sites samples in Lake Wolsey, 2011

Survey	Station	Water Depth (m)	DIC (mg L ⁻¹)	DOC (mg L ⁻¹)	TSS (mg L ⁻¹)	Silicate (mg L ⁻¹)	pH	Chloride (mg L ⁻¹)	Conductivity (25°C) (µSiem cm ⁻¹)	Alkalinity (mg L ⁻¹)	Turbidity (FTU)	Secchi (m)
6-May-11	229	16.8	23.8	2.9	1.6 ^T	1.8	8.39	5.3	240	96.2	0.82	3.7
	595	22.9	23.6	2.8	2.4	1.8	8.38	5.3	239	96.4	0.87	1.8
	596	19.5	23.4	2.9	1.9 ^T	1.8	8.37	5.1	239	95.4	0.75	3.6
	598	20.7	23.1	2.8	2.1 ^T	1.7	8.38	5.4	239	95.3	0.82	3.3
9-Aug-11	229	16.8	23.1	3.0	1.0 ^T	1.4	8.47	5.6	235	93.5	0.53	4.2
	595	23.5	22.9	2.9	0.9 ^T	1.4	8.47	5.4	236	93.9	0.51	4.2
	596	18.2	22.9	3.0	1.2 ^T	1.4	8.46	5.7	235	93.7	0.52	4.5
	598	22.4	22.7	2.9	1.1 ^T	1.4	8.43	5.6	236	93.2	0.50	4.1
25-Oct-11	229	16.7	22.7	2.6	1.9 ^T	1.8	8.29	5.8	233	96.3	0.88	2.4
	595	22.8	22.8	2.6	1.9 ^T	1.8	8.29	5.1	233	96.5	0.82	2.5
	596	18.9	22.7	2.6	1.9 ^T	1.8	8.29	5.3	234	96.3	0.85	2.7
	598	21.7	22.2	2.6	3.7	1.7	8.29	5.1	232	96.0	0.66	3.1

3.4 Physical Structure

3.4.1 Thermal Structure

Summer stratification is an important process because the partitioning of the water column into different thermal layers can have important implications on the distribution, behaviour and life-cycle processes of aquatic biota. Temperature information can provide insight on the physical structure of the water column by identifying the boundary conditions of these water masses.

From 2007 to 2011 we deployed real-time continuous *in situ* temperature sensors in 1 m to 3 m increments at various locations in Lake Wolsey. Temperature data were also available with select real-time sensors including dissolved oxygen sensors, turbidity/chlorophyll a sensors and water level loggers. All of the temperature data were combined and averaged by hour and by day to facilitate data analysis. We calculated the water density from the temperature data in order to derive the density profiles which were then used to determine if a) the water column is stratified and b) the boundary depths of each of the water masses c) volume-weighted average temperature and dissolved oxygen for each of the water masses.

Thermal stratification occurred at all stations, including the shallower stations such as the near-cage site (Stn 596). We found the water column was stratified by early June and remained stratified until September/October (Table 9). The stratification period varied between site and year. For the deep proximal site (Stn 595) the water column was stratified for 93 to 111 days, while the shallower near-cage site (Stn 596) experienced a shorter stratification period ranging from 83 to 90 days. The onset of stratification occurred at the same time for both sites, however fall turnover was found to vary between the two. Although there are interannual differences in stratification patterns and length, we found the stratification period was similar in 2008 and 2010.

Table 9 Summary of the stratification features of the deep proximal site (Stn 595) and near-cage site (Stn 596) based on the real-time continuous *in situ* temperature (°C) data collected between 2007 to 2009, Lake Wolsey

Year	Station	Stratification period	No. of stratified days	Averaged Density Difference	Averaged Mixing Depth (m)	Averaged Temperature (°C)	
						Epilimnion	Hypolimnion
2007	595	Jun 12 - Sept 12, 2007	93	0.76	17.5	20.1	16.0
2008	595	Jun 12 - Oct 01, 2008	111	1.23	14.7	20.4	14.8
	596	Jun 12 - Sept 06, 2008	83	1.05	12.0	20.1	15.9
2009	595	Jun 15 - Sept 28, 2009	106	0.75	13.3	18.9	14.5
	596	Jun 15 - Sept 17, 2009	90	0.66	11.7	19.1	15.3

We used daily-averaged temperature with depth data to generate graphs of temperature, depth and time to better understand the thermal structure of the water column vertically and through time (Figure 19, Figure 20, Figure 21, Figure 22). These graphs provide a comprehensive overview of the thermal structure of the water column through the ice-free season.

Lake Wolsey exhibits typical warming and cooling patterns. Spring-time conditions are cooler and warm during the summer season. By mid-June surface water temperatures exceeded

20°C. Surface waters generally peak in August and begin to decline by mid-September with continued surface water cooling in the fall with temperatures below 10°C by early-November.

In 2007, the water column was thermally stratified by June 12, 2007 and we found the hypolimnion to be relatively warm (> 14°C) (Figure 19). The thermocline deepened over time and by mid-August Lake Wolsey waters exceeded 20°C and this warming extended to 20 m. In 2008, the surface waters did not warm up as rapidly as in 2007 and water temperatures did not exceed 20°C until early July, however stratification occurred three days earlier. The water column was more stable and water temperatures exceeded 20°C from surface to ~ 14 m depths from late-July to early September. In 2008, fall turnover occurred ~ 2 to 3 weeks later than 2007. Thermal patterns were similar between stations in 2008, however at the near-cage site (Stn 596) the warmer waters (> 20°C) extended deeper in the water column (Figure 20).

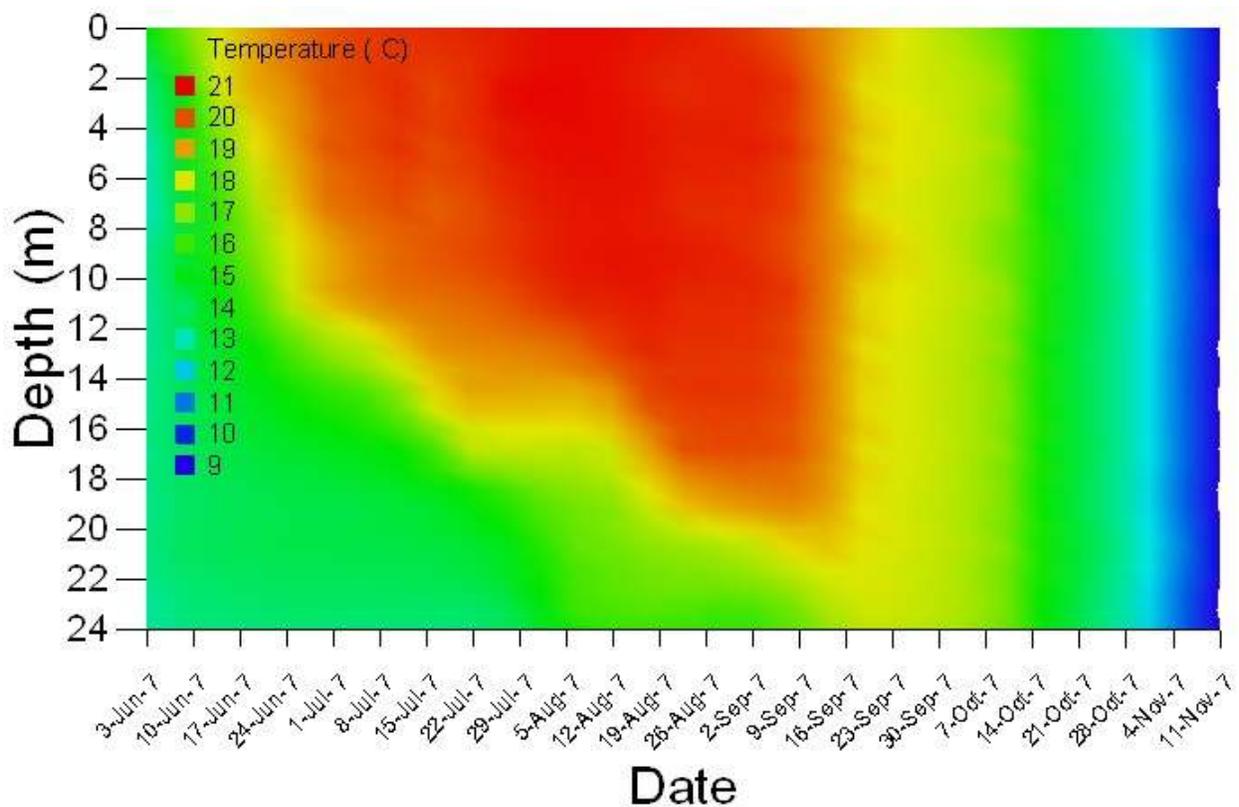


Figure 19 Station 595 daily averaged temperature (°C) with depth (m) and over time over the 2007 ice-free season

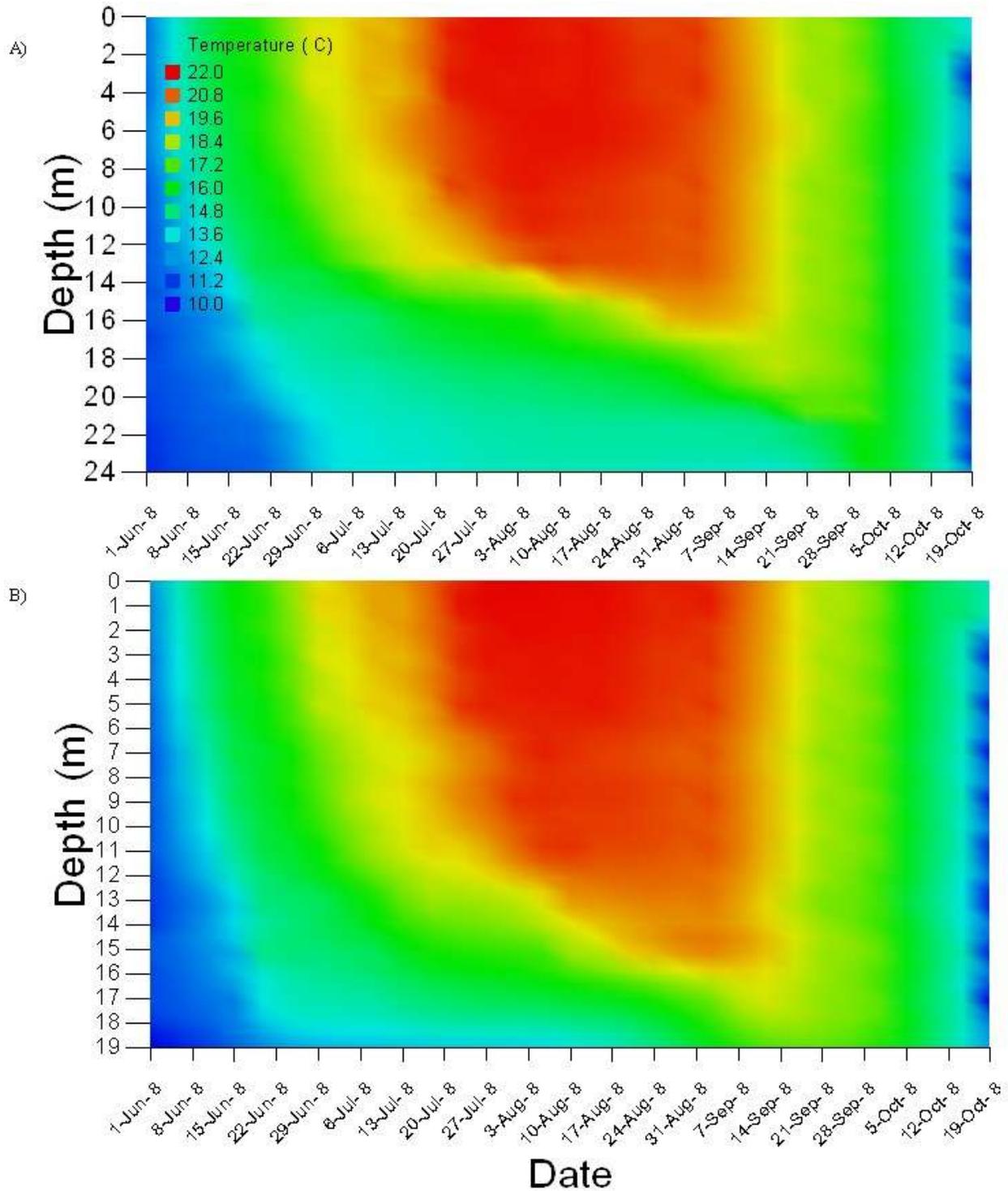


Figure 20 Daily averaged temperature (°C) with depth (m) and over time for a) Station 595 and b) Station 596 over the 2008 ice-free season

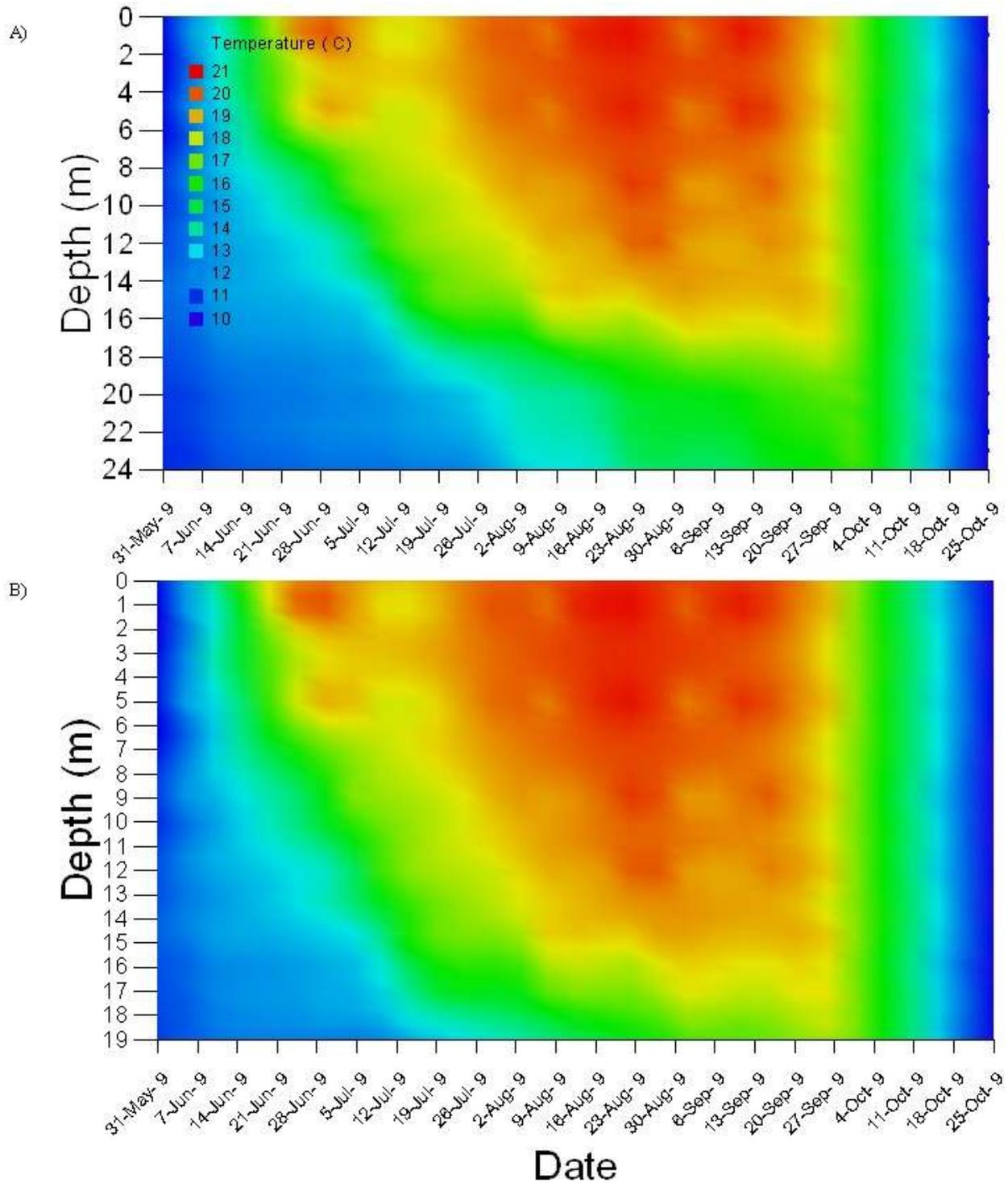


Figure 21 Daily averaged temperature (°C) with depth (m) and over time for a) Station 595 and b) Station 596 over the 2009 ice-free season

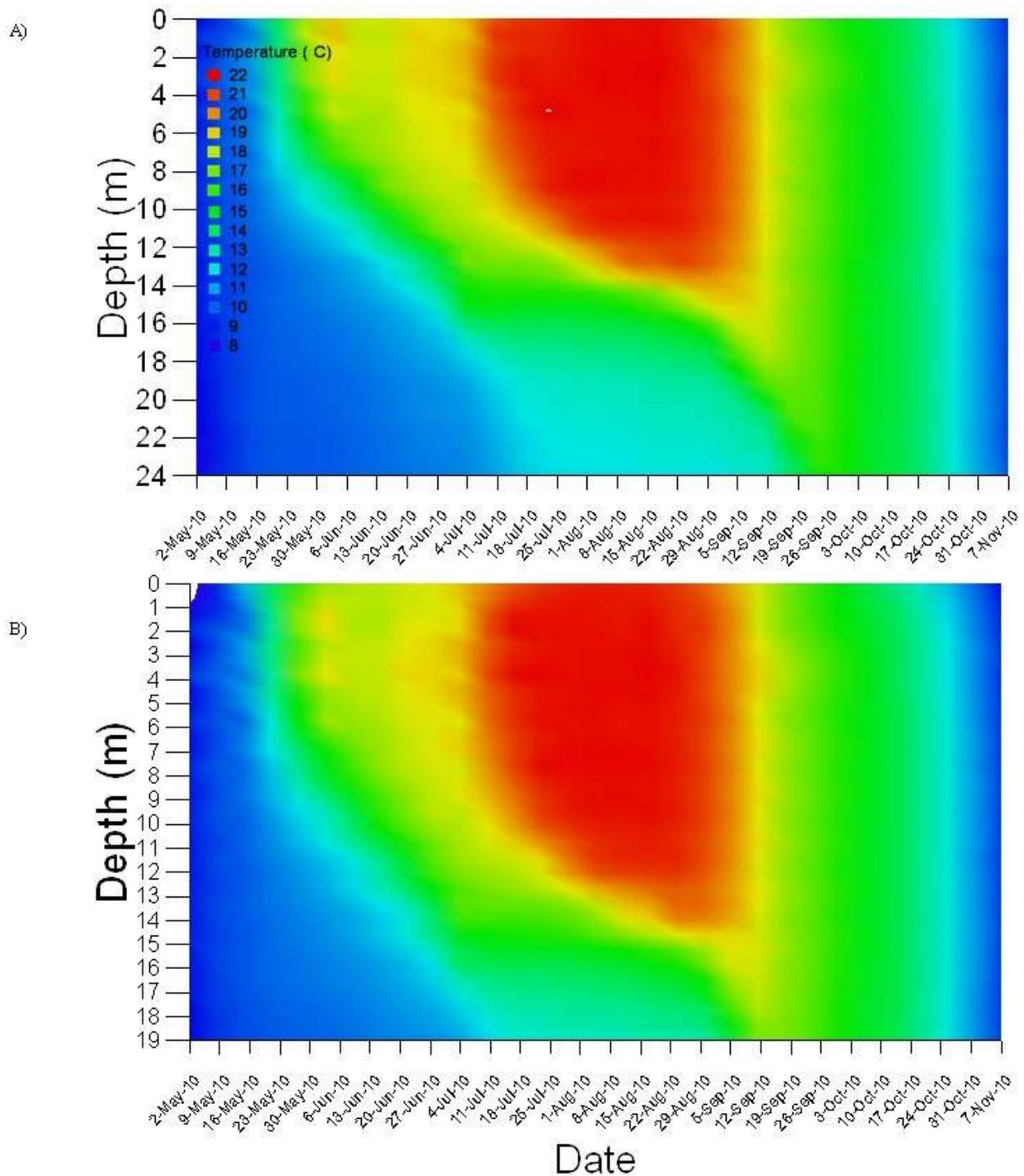


Figure 22 Daily averaged temperature (°C) with depth (m) and over time for a) Station 595 and b) Station 596 over the 2010 ice-free season

In 2009, the waters of this embayment were cooler than in 2007 and 2008. By mid-June the water column was weakly stratified, but was thermally stable by mid-July (Figure 21). Surface

water warming did occur and extended to 16 m, however water temperatures were not consistently greater than 20°C. Stn 596 displayed the same thermal pattern over time.

In 2010, we deployed additional thermistor chains on the southside of the cage aquaculture operation and near the culvert. As observed in 2009, the surface waters did not exceed 20°C until early July despite stratification occurring 2 to 3 weeks earlier than the previous years (Figure 22). We found the surface mixed layer to be stable and extended to ~14 to 15 m. By mid-September the waters were isothermal after fall turnover. These thermal patterns were consistent between sites.

Due to the depth difference between stations, it is not surprising that the number of stratified days varies between the two sites with the deep site, Station 595, generally exhibiting a longer stratified season (~20 days) than the shallower site, Station 596 (Table 9). Although the onset of stratification occurs at the same time as the deep proximal site (Stn 595), the shallower near-cage site experiences fall turnover earlier due to deepening of the thermocline.

We calculated water density from the high resolution temperature data and used this information to determine stratification patterns and density time trends. Large differences in density between the water masses (e.g., epilimnion, hypolimnion) will inhibit mixing between the water masses. The difference between hypolimnetic water density and epilimnetic water density was plotted over time for each station (Figure 23) to ascertain temporal and spatial patterns in water density. Water density patterns were found to be variable within year and between years. Although the density patterns between stations were similar in 2010, this was not the case for 2008 and 2009. In 2008/09, Stns 595 and 596 density patterns were closely aligned early in the ice-free season, however diverged by mid to late summer. Density differences were weaker at the near-cage site (Stn 596) compared to the deep proximal site (Stn 595), therefore the shallower near-cage site is likely more susceptible to mixing than the deeper site, as evident by earlier fall turnover. Stn 596 also exhibited higher daily variability (Figure 23). Sharp declines in the density difference marked the occurrence of fall turnover at Stn 595, however in 2008/09, these declines were more gradual for the near-cage site (Stn 596). Maximum density differences occurred at different times of the year and ranged from 1.60 to 2.21. This difference was greatest in 2010 and was generally lower at the shallower sites compared to the deep site (Stn 595).

We also used the temperature/density data to determine the boundary depth that separates the hypolimnion from the metalimnion and epilimnion. The hypolimnetic boundary depth was plotted against time to compare spatial and temporal trends. The hypolimnetic boundary depth, or top of the hypolimnion, was determined using the density approach and was determined for Stations 595 and 596 and plotted against time (Figure 23). The temporal pattern in hypolimnetic depth varied between and within years (Figure 26, Figure 27). The onset of stratification occurred in mid-June for all years; however the initial hypolimnetic volume in 2009 was large, with a hypolimnetic depth < 10 m at the onset of stratification. Only in August was the hypolimnetic depth similar for each station across years. As expected gradual deepening of the thermocline occurred in late-summer, however patterns varied between years and fall turnover occurred later in 2008 and 2009.

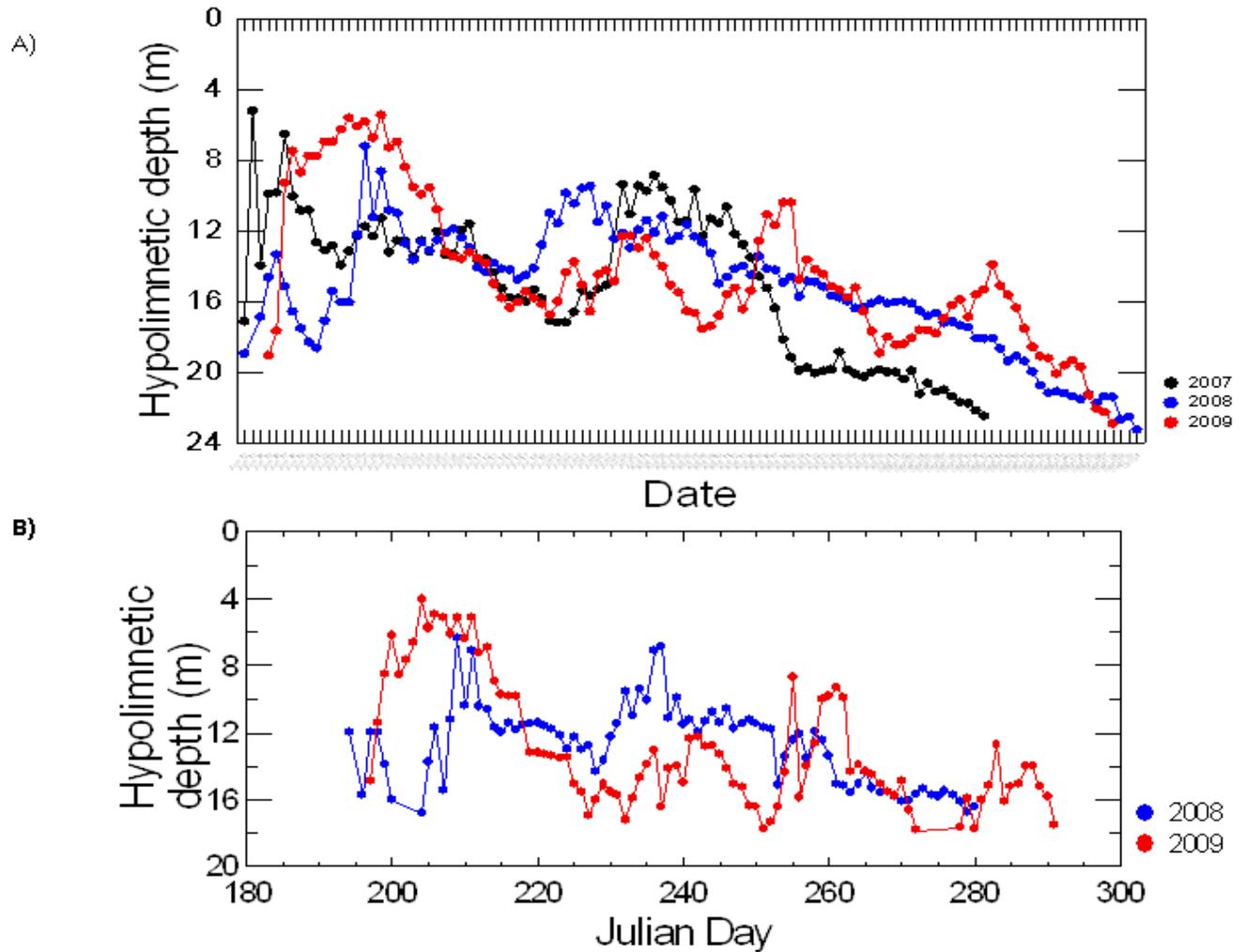


Figure 23 Hypolimnetic depth (m) of the a) deep proximal site (Stn 595) from 2007 to 2009 and b) near-cage site (Stn 596) in 2008 and 2009, Lake Wolsey

An understanding of the hypolimnetic thickness dynamics provides us insight on the dissolved oxygen dynamics because the hypolimnetic thickness determines hypolimnetic volume and the amount of dissolved oxygen that is available in the deep cooler waters. Since seasonal patterns varied widely between years and to facilitate comparison to other studies, we converted the hypolimnetic boundary to hypolimnetic thickness, which is the difference between the hypolimnetic boundary and maximum station depth. Between 2007 and 2009 the hypolimnetic thickness varied widely in early summer (Figure 23). The hypolimnetic thickness was generally larger at Stn 595 compared to Stn 596, and ranged from 8.3 m to 16.9m, 10.2 m to 11.5 m in June and July, respectively. The hypolimnetic thickness stabilized in August with values ranging from 8.7 m to 9.4 m. The hypolimnetic thickness varied widely in September with

values ranging from 2.8 m to 6.1 m, due to the deepening of the thermocline with fall turnover generally occurring in mid-September to early October.

The hypolimnetic depths between stations is similar in early to mid-summer, however the deep station (Stn 595) is more strongly stratified than the shallower station (Stn 595) with comparatively greater density differences between the epilimnion and the hypolimnion (Figure 24). Density differences begin to diminish by late-summer with deepening of the thermocline until the thermocline exceeds maximum station depth or fall turnover, resulting in isothermal conditions.

Although hypolimnetic dissolved oxygen depletion could be expected to be exacerbated by an extended duration of summer stratification, hypolimnetic anoxia still occurred in 2007 despite the shorter stratification period. We note, however, that deepening of the thermocline occurred earlier in 2007 compared to 2008/09 limiting the assimilative capacity of the hypolimnion. This suggests that it is relevant to consider both the duration of stratification and the temporal dynamics of the hypolimnetic depth when considering factors that influence the potential for hypolimnetic dissolved oxygen depletion.

These graphs provide a concise overview of the changes in the thermal structure which allow for spatial and temporal comparisons. At all stations, the water column was thermally stratified with a hypolimnion that persisted until September/October. From these data we can conclude that the thermal structure is similar between sites, however there are interannual differences including changes in the extent of mixed layer warming, onset of stratification and fall turnover. The waters of Lake Wolsey are warm, with surface waters exceeding 20°C during the summer stratified season. Lake Wolsey is generally stratified for 3 to 4 months during the ice-free season with onset of stratification generally occurring in June and fall turnover occurring between mid-September to early October. From the temperature data we were able to identify the boundary conditions of the epilimnion, metalimnion and hypolimnion. This embayment is not thermally static and the hypolimnion was found to fluctuate widely during the ice-free season. Interannual differences were also evident, however spatial differences were minimal.

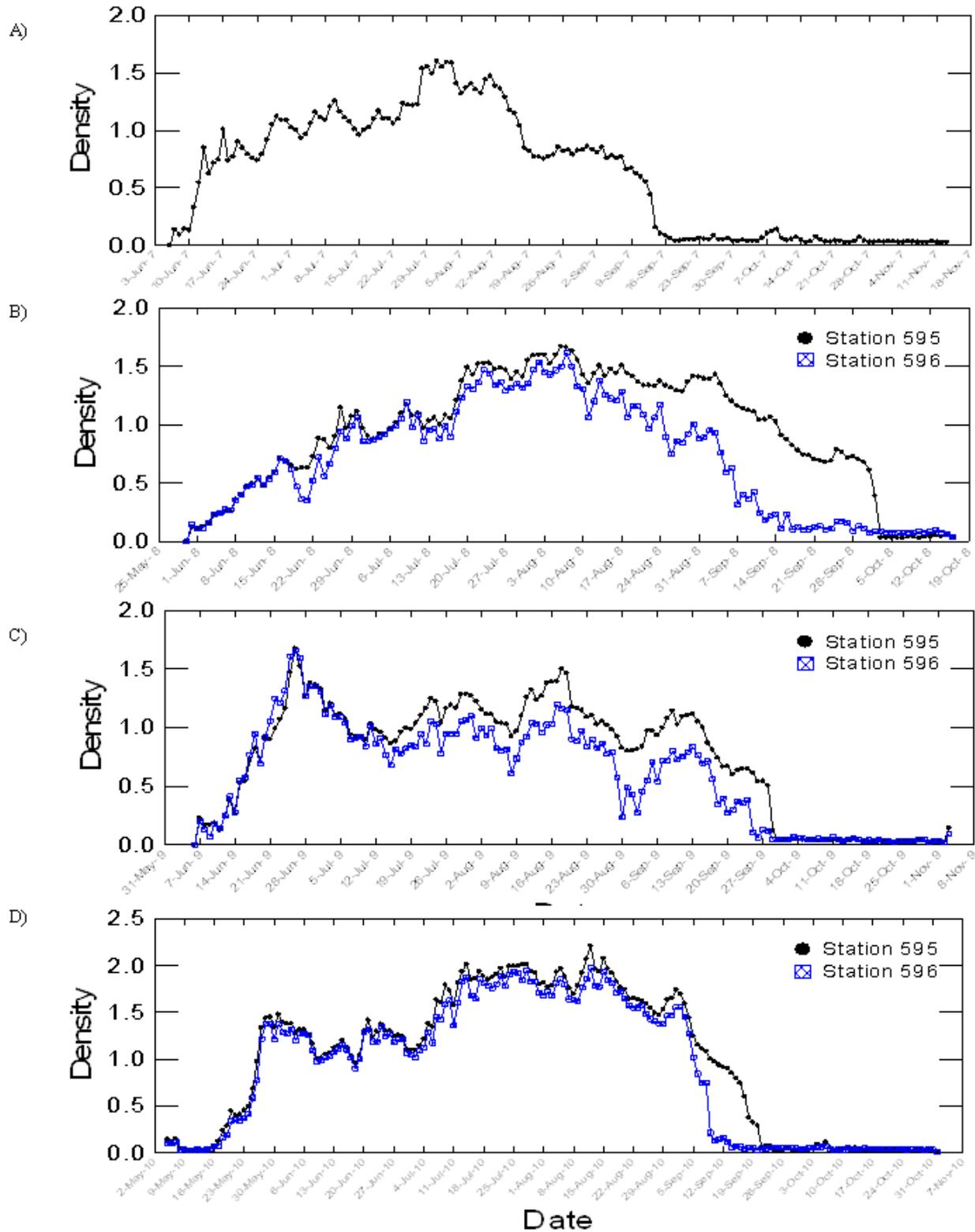


Figure 24 Daily density differences between the hypolimnion and epilimnion for a) 2007 b) 2008 c) 2009 and 2010 ice-free season, Lake Wolsey

3.4.2 Water Level

For waterbodies with restricted access to the open waters changes in water level can have a large effect on its ability to tolerate change with lower water levels decreasing the aquatic system's ability to tolerate additional nutrient loadings, increasing its susceptibility to hypolimnetic dissolved oxygen depletion (Merilainen *et al*, 2000). Lower water levels can also increase the thermal regime of a lake, by increasing the susceptibility to warming, thereby resulting in waters that are less soluble to dissolved oxygen.

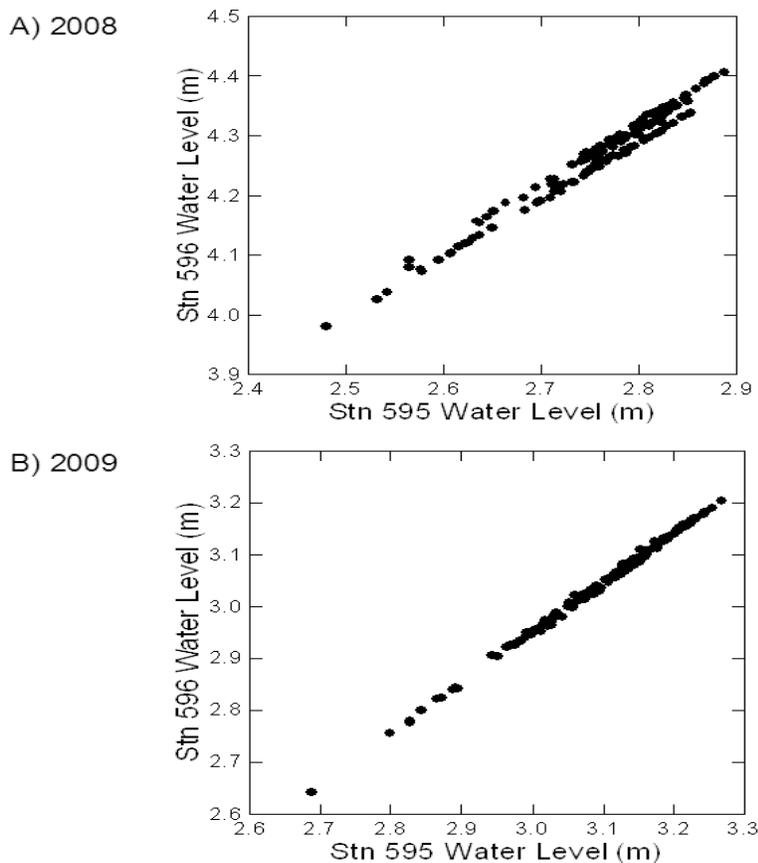


Figure 25 The relationship between the deep proximal site (Stn 595) and near-cage site (Stn 596) water level in A) 2008 and B) 2009, Lake Wolsey

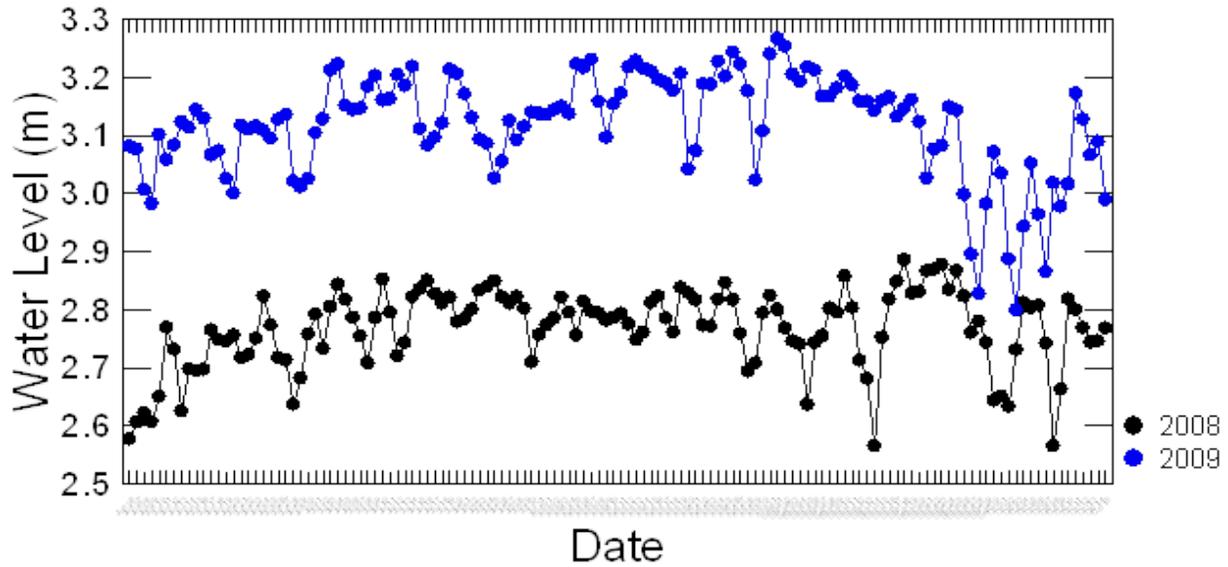


Figure 26 Daily-averaged water level (m) at 3.0 m below water surface at Station 595 (deep site) during the ice-free season in 2008 and 2009, Lake Wolsey

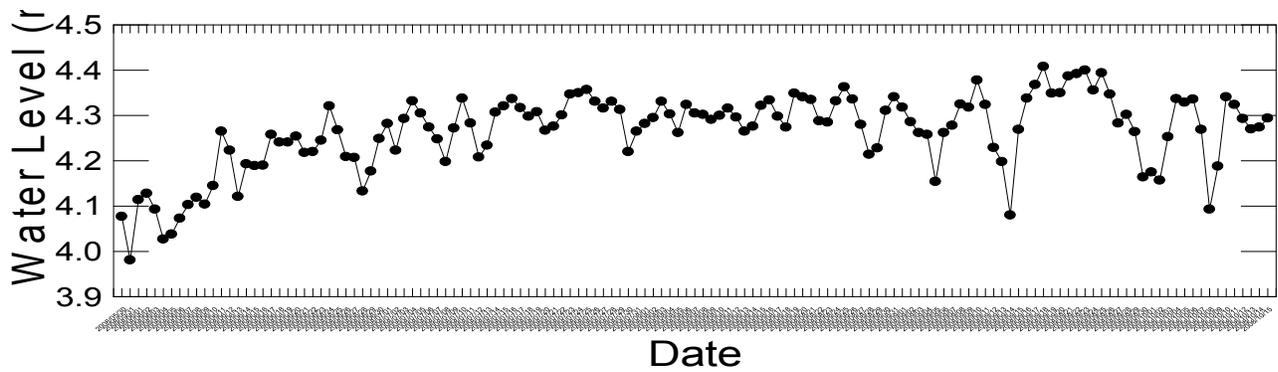


Figure 27 Daily-averaged water level measurements at 4.0 m at the near-cage site (Station 596) during the 2008 ice-free season (May 30 - October 15, 2008), Lake Wolsey

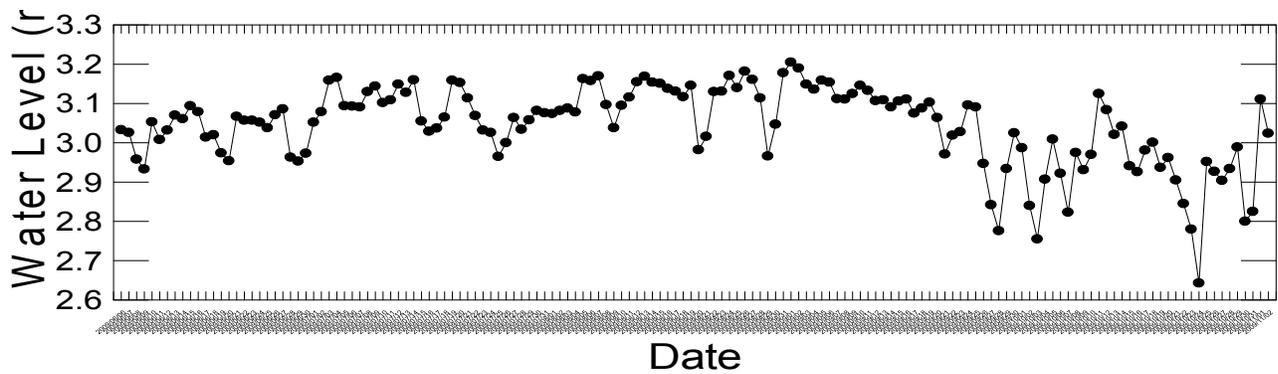


Figure 28 Daily-averaged water level measurements at 3.0 m at the near-cage site (Station 596) during the 2009 ice-free season (June 06 - November 02, 2009), Lake Wolsey

Water level loggers deployed in close proximity to the deep basin revealed a system that is hydrologically dynamic. Water level fluctuations were found to be similar between stations. There was good agreement between stations and the temporal patterns in water level fluctuations were similar between stations (Figure 25), however, the water level fluctuations were slightly higher for the shallower near-cage station (Stn 596). The high correlation in water level between stations suggests that the spatial variability in water level within Lake Wolsey is low.

Daily fluctuations in water levels were observed with water level patterns varying between years (Figure 25, Figure 28). Water levels were found to fluctuate by 0.4 m in 2008 and 0.6 m in 2009 with standard deviation of ~ 0.1 m . Although the range in water level may be considered small, it has the potential to affect the hydrology and residence time of the system. Water levels were generally higher in 2009 compared to 2008, therefore Lake Wolsey likely possessed comparatively higher assimilative capacity and resilience in 2009 (Figure 11).

3.4.3 Bathymetry

The 2006 survey found Lake Wolsey to be smaller and deeper than previously estimated by Gale (1999) with a surface area of 2033 ha compared to the original estimate of 2315 ha. The estimated volume of Lake Wolsey is also smaller with a volume of 244 250 264 m³ compared to Gale's (1999) estimate of 263 760 000 m³. Our estimate of the mean depth, based on lake surface area and volume, is 12.0 m and this is higher than previous estimates of 11.4 m (Gale, 1999) and 8.5 m (Milne et al, 2015).

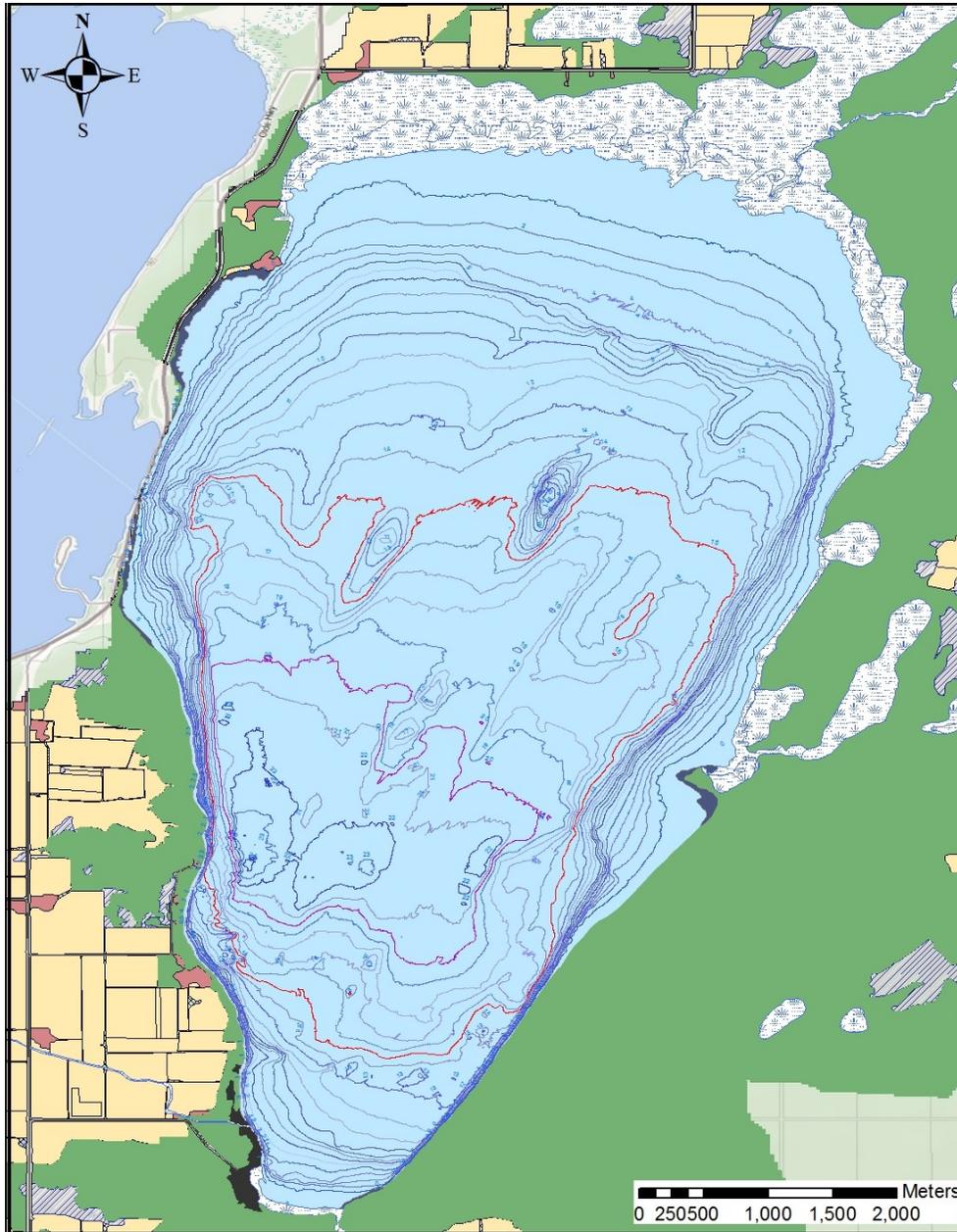


Figure 29 Bathymetry map of Lake Wolsey, in one-meter, based on the 2006 MOECC/MNRF Bathymetry Study. Line indicates the 15 m (- -) and 20 m (- -) depth contours.

Lake Wolsey possesses a large littoral zone, with the 0 to 5m depth strata accounting for over 30% of the total volume (Figure 29). The deep basin is located in the southwest region of the lake and is in close proximity to the cage aquaculture operation, shoreline residences and agricultural lands.

According to the IJC (2009), water levels dropped from ~ 176.4 to 176.1. This 0.3 m drop in water level between 1999 to 2006 may partially explain the discrepancy between the 2006 and

the 1999 volume and surface area estimates. Based on these bathymetry results we estimate the residence time for Lake Wolsey is likely 294 days, which is 79 days longer than previously reported (Hamblin & Gale, 2002; Clerk, 2001, Milne et al, 2015).

3.5 Dissolved Oxygen

3.5.1 Dissolved Oxygen: Real-time Monitoring

In Ontario, the Provincial Water Quality Objectives (PWQOs) for dissolved oxygen (DO) are minimum numerical limits for the protection of warm and cold-water biota (MOE, 1994). PWQOs of 6 mg L⁻¹ (54%) and 4 mg L⁻¹ (47%) are set for the protection of cold-water and warm-water biota respectively. The surface waters of natural waterbodies are generally saturated with dissolved oxygen (Wetzel, 2001) and data from the real-time continuous sensors indicate that this was the case for Lake Wolsey in early summer and for epilimnetic waters. The surface waters of Lake Wolsey were generally DO saturated, with average DO levels of > 7 mg L⁻¹ during the ice-free season between 2008 and 2011 (Error: Reference source not found- Error: Reference source not found). However, declines in DO were observed episodically throughout the year with minimum DO levels of 3.2 mg L⁻¹, 0.1 mg L⁻¹ and 3.0 mg L⁻¹ in 2008, 2009 and 2010, respectively. Except for 2010, the shallower stations were found to exhibit lower surface water DO levels compared to the deeper site. In 2009, hourly-averaged DO data indicated anoxic conditions were occurring episodically from August 17 to 24 at the deep site (Stn 595) and in early to mid-October at the near cage site (Stn 596).

DO sensors deployed at ~ 15 m to 18 m captured mid-water column DO conditions and at 21 to 23 m captured bottom water DO conditions. We observed anoxic conditions at all sites with DO values below 1 mg L⁻¹ (Error: Reference source not found- Figure 33), indicating severe DO depletion annually across the basin. Once initiated, the anoxic condition persisted until fall turnover and DO levels returned to above the PWQOs and saturated conditions (Error: Reference source not found- Figure 33). Anoxic conditions was observed in the hypolimnetic bottom-waters of the entire basin and was found to extend up to mid-water column depths, hence is spatially and vertically widespread in this embayment.

From this data we calculated the daily-averaged DO concentrations to estimate the number of hypoxic (< 4 mg L⁻¹) and anoxic days (<1 mg L⁻¹) for each station and at each depth across years to determine the onset, extent and duration of hypoxia and anoxia. At 17 m below water surface, anoxic conditions were observed and persisted for 20 to 32 days, or 22% to 39% of the

2007 and 2008 summer stratified season. The anoxia extended up to 15 m at the near-cage site (Stn 596) in 2008 and persisted for 27 days or 33% of the summer stratified season. In 2008, the near-cage site experienced 27 and 32 days of anoxia, which is substantially longer than observed at the deep site (. In 2010, the DO condition at ~ 18 m, which is ~ 1m above bottom for Stations 596, 229 and 598 reached hypoxic and anoxic levels. Stations 596 and 598 experienced substantially longer periods of anoxia (16 to 18 days) compared to Station 229, however the number of hypoxic days were relatively similar between the three sites (39 to 44 days). DO sensors were also deployed at 16.9m and 15.7 m at Stations 595 and 596, respectively. Although the number of anoxic days was slightly higher for the deep site (Stn 595), the near-cage site experienced a greater number of hypoxic days, which is surprising given the near-cage sensor was ~ 1 m shallower than the deep site. Sensors deployed in the bottom waters of Lake Wolsey (~22m) exhibited hypolimnetic dissolved oxygen depletion shortly after stratification that persisted until fall turnover (Figure 30, Figure 31, Error: Reference source not found, Error: Reference source not found, Figure 33, Figure 34). The maximum number of anoxic and hypoxic days occurred in 2008, with 57 anoxic days and 81 hypoxic days. Bottom-water anoxia was observed from 2007 to 2009 and persisted for 45 to 57 days, or 42% to 52% of the summer stratified season. In 2010, the bottom waters of Lake Wolsey experienced anoxia for only 33 days or ~27% of the summer stratified 2010, partially because the anoxia did not set up until much later in the year compared to the other years. However similar to the previous years, once anoxic it remained in this condition until fall turnover.

Table 10 Dissolved oxygen concentration (mg L^{-1}) for Station 595, 596, 229 and 598 for the ice-free season between 2007–2010

Year	Station	Sensor Depth (m)	Dissolved Oxygen (mg L^{-1})			No. Anoxic Days	No. Hypoxic Days
			Minimum	Maximum	Range	(<1 mg L^{-1})	(< 4 mg L^{-1})
2007	Station 595	16.8	0.3	8.4	8.1	20	51
		20.8	-0.1	10.7	10.8	48	75
2008	Station 595	5	5.7	10.5	4.8	0	0
		15	0.7	10.6	9.9	0	35
		17	0.0	11.8	11.8	5	38
		23	0.0	11.2	11.2	57	81
	Station 596	5	3.2	10.0	6.8	0	0
		15	0.1	10.0	9.8	27	59
17		0.2	9.8	9.6	32	63	
2009	Station 595	5	0.9	13.7	12.8	0	0
		15	0.5	15.0	14.5	0	17
		17	0.4	11.3	10.9	0	34
		22	0.1	13.6	13.6	45	60
	Station 596	5	0.1	15.7	15.6	2	7
		15	0.5	11.1	10.6	0	34
17		-0.1	12.5	12.6	0	51	
2010	Station 595	4.9	3.9	12.0	8.1	0	0
		16.9	0.4	12.0	11.6	13	38
		21.9	0.3	12.0	11.7	33	55
		21.6*	0.2	12.3	12.2	na	na
		21.1**	0.0	11.0	11.0	na	na
	Station 596	5.7	4.3	13.2	8.9	0	0
		15.7	0.4	13.4	13.0	11	47
		17.7	0.0	12.6	12.6	16	44
		17.2**	-0.5	11.0	11.4	na	na
	Station 229	5.8	4.5	12.6	8.2	0	0
		17.8	0.1	11.6	11.5	1	39
	Station 598	6	3.0	12.1	9.1	0	0
		18	0.4	12.2	11.8	18	42

* ** Optical dissolved oxygen sensors

The bottom waters of Lake Wolsey were hypoxic and fell below the dissolved oxygen Provincial Water Quality Objectives (PWQOs) for the majority of the summer stratified season and this condition extended up to 13.6 m below the water surface in 2008. In 2007, hypoxia (< 4 mg/L) was observed at 16.8m for 48% of the stratified season. In 2008, hypoxia was observed at 15 to 16 m for 38% and 77% of the summer stratified season at the deep proximal site (Stn 595) and near-cage site (Stn, 596), respectively. Although anoxic conditions were not observed at 15m in 2009, the waters were hypoxic and this hypoxia persisted for 22% and 40% of the summer stratified season for the deep proximal site (Stn 595) and near-cage site (Stn 596), respectively.

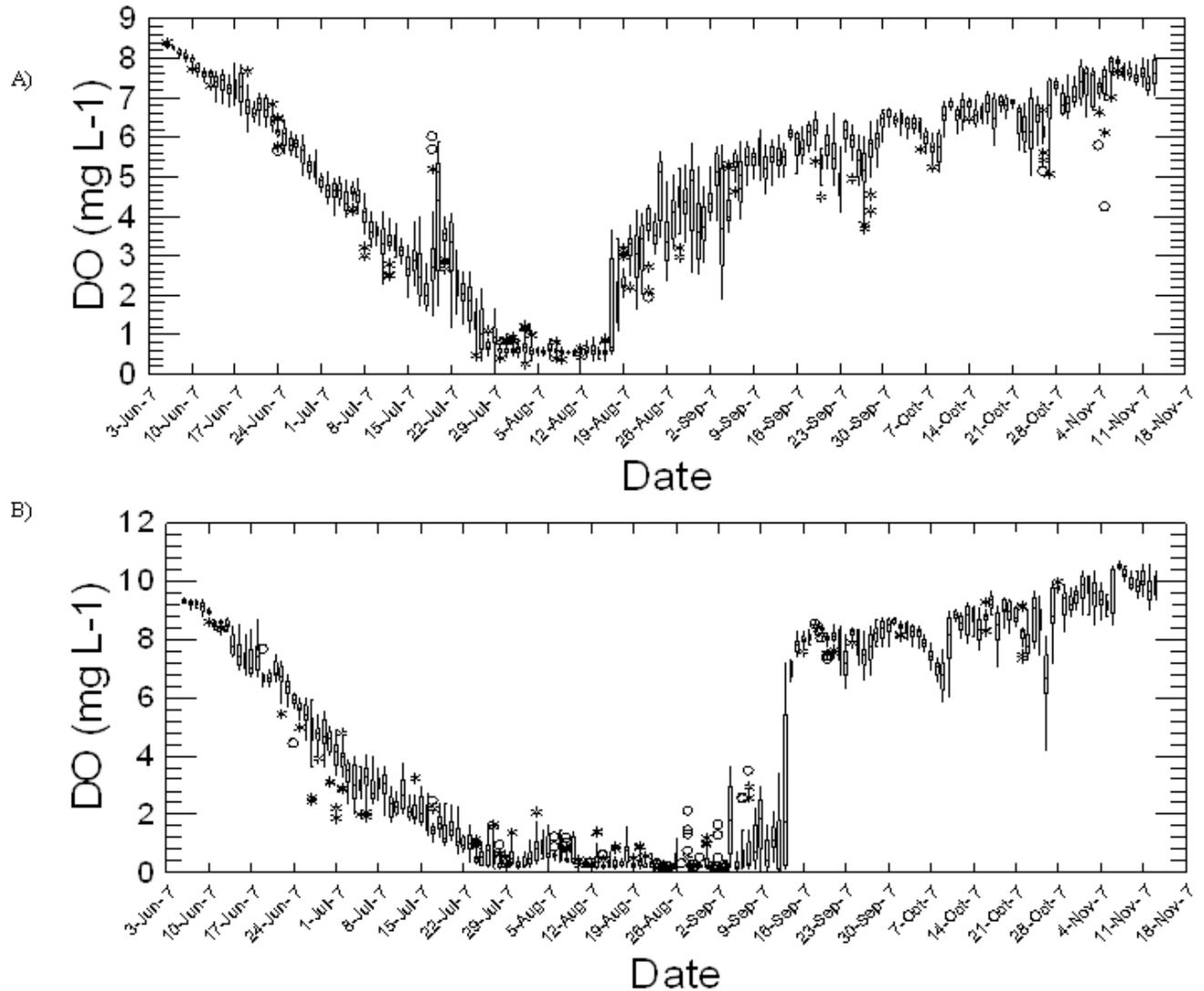


Figure 30 Dissolved oxygen (mg L^{-1}) trends at Station 595 at a) 16.8 m and b) 20.8 m during the 2007 ice-free season, Lake Wolsey

In 2010, we also deployed optical and membrane sensors at Stations 595 and 596 in late-summer to compare to data collected by the membrane-style DO sensors that were deployed in the spring. We found good correspondence between the optical and membrane sensors deployed at the near-cage site (Stn 596) for DO concentrations $> 7 \text{ mg L}^{-1}$. At the lower DO spectrum the optical sensor detected higher levels of DO compared to the membrane sensors, possibly due to its placement in the water column. The optical sensor was deployed at 17.2 m, which is 0.5 m shallower than the location of the membrane sensor. At the deep proximal site (Stn 595) there was also good correspondence between the two sensor types for DO greater

than 8 mg L^{-1} , however for DO less than 8 mg L^{-1} , the membrane sensor detected higher levels of DO compared to the optical sensor. Since optical sensors are generally more robust than membrane sensors in anoxic waters it is likely that the membrane sensor is overestimating the amount of DO available in the water column. In late-summer, we deployed an additional membrane sensor in the bottom waters of the deep proximal site to compare to the membrane sensor deployed in the spring and to compare to the optical sensor data. We found good agreement between this membrane sensor and the optical sensor, however the membrane sensor did, on average, overestimate DO levels by 0.8 mg L^{-1} . When compared to the recently deployed membrane sensor, the sensor deployed in the spring was found to overestimate the amount of DO available by 0.4 mg L^{-1} . This data suggests there may be some drift over time with the membrane sensors potentially overestimating the amount of oxygen available in the water column. It also suggests that on a performance level, for systems that experience hypoxia or anoxia optical sensors may be more ideal under these circumstances since membrane sensors have the potential to overestimate DO levels.

When we compared bottom-water DO levels from 2007 to 2010 we noted differences in the rate at which the bottom waters reach anoxic conditions and the duration of anoxia. From our analysis we determined that 2010 experienced the shortest anoxic period (33 days) and 2008 the bottom waters experienced the longest anoxic period (57 days) and is a function of DO depletion rates and stratification length. In 2010, the water column was stratified from May 19 to September 20th, and was stratified for 124 days; however the duration of anoxia was shorter than 2008 even though the stratification period was 118 days. This may be due to the timing of the stratification period. In 2010, the water column was stratified by mid-May with fall turnover occurring on September 20th. In 2008, the water column stratified later, around June 06, however fall turnover occurred at the beginning of October.

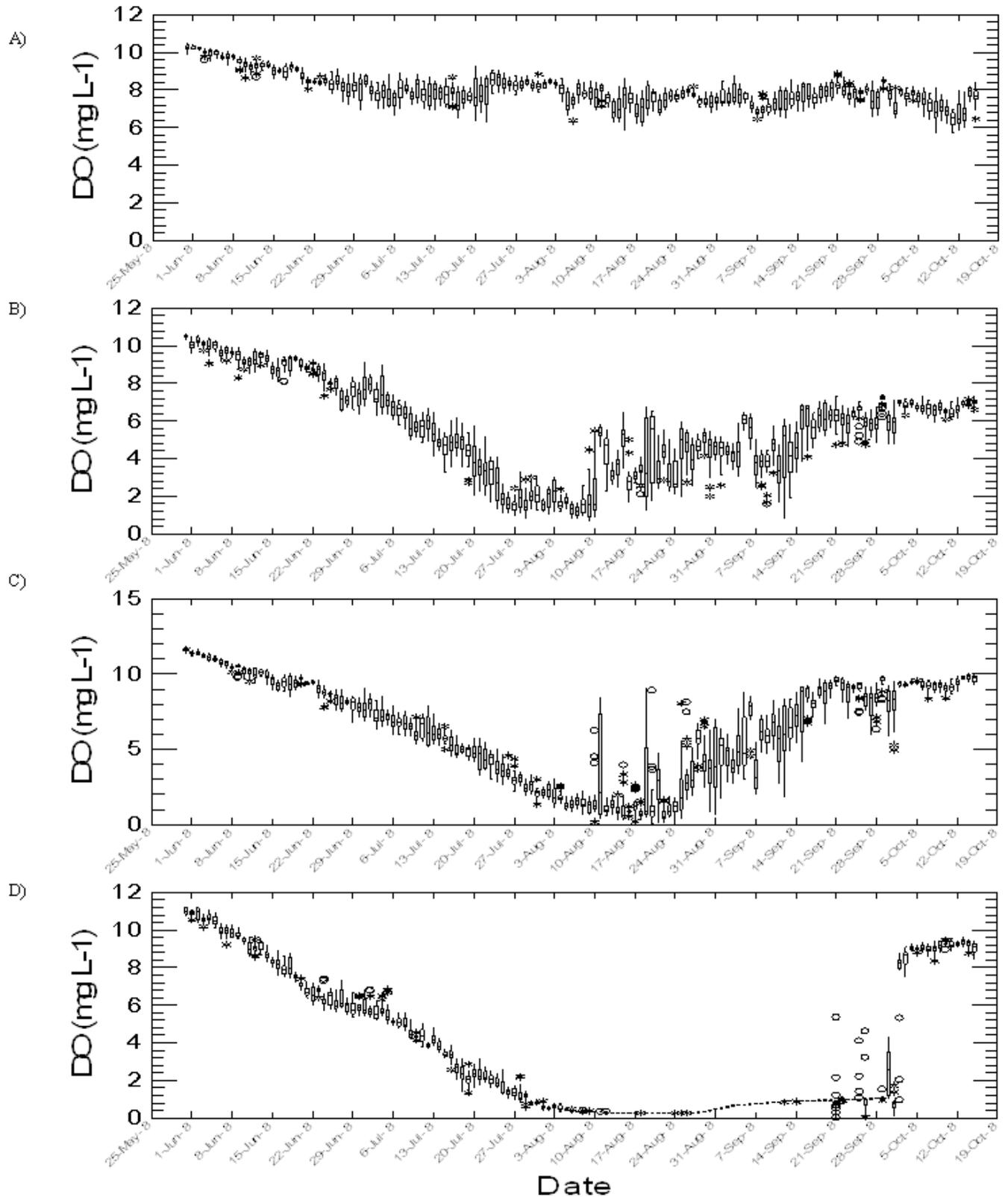


Figure 31 Dissolved oxygen (mg L⁻¹) trends at Station 595 at a) 5 m b) 15 m c) 17 m and d) 23 m during the 2008 ice-free season, Lake Wolsey

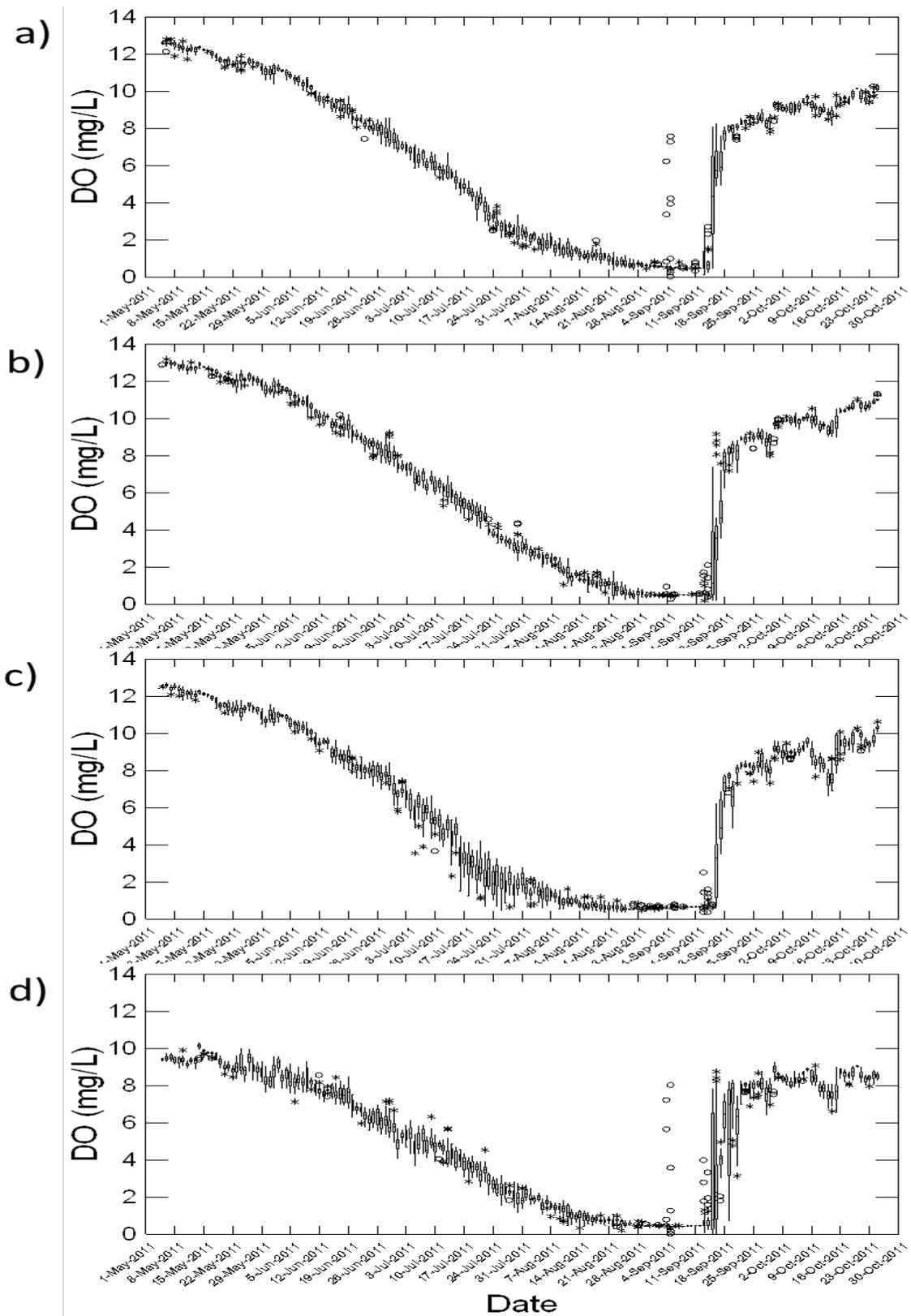


Figure 32 Mid-column (16 – 18 m) dissolved oxygen (mg L^{-1}) concentration Stations a) 595 b) 596 c) 598

and d) 229 during the 2011 ice-free season, Lake Wolsey

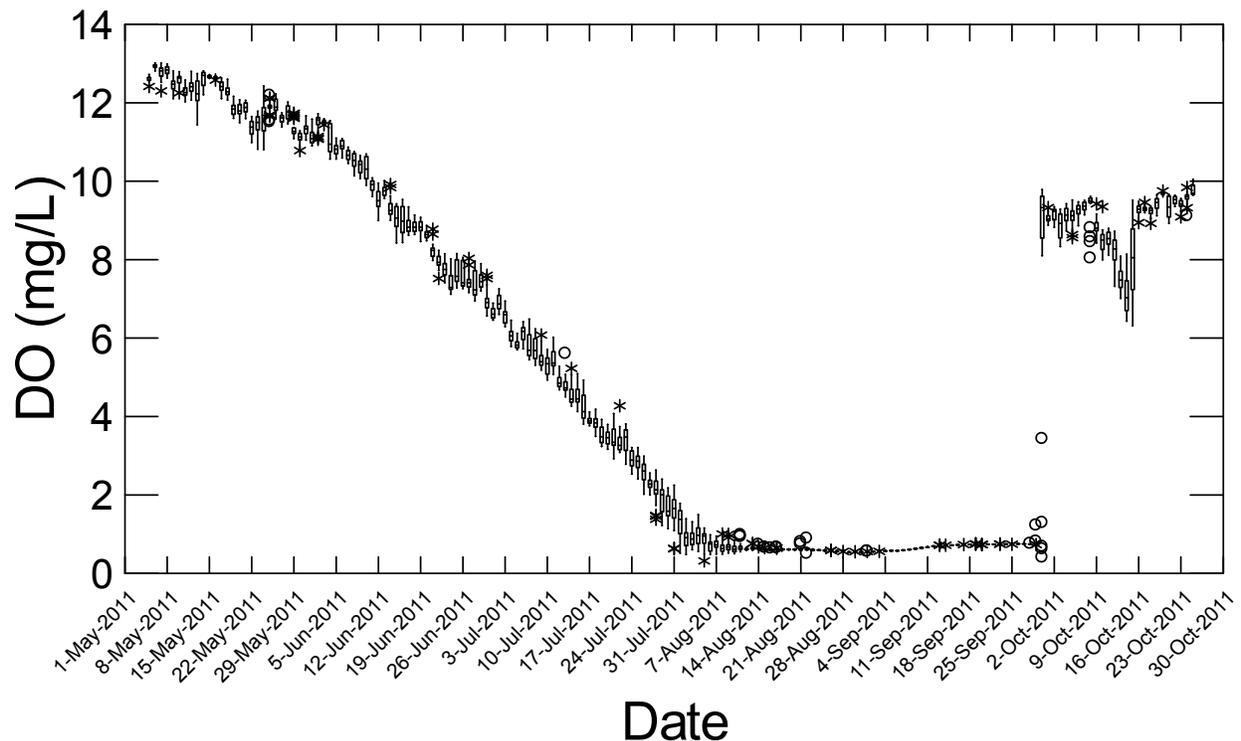


Figure 33 Bottom-water (21 m) dissolved oxygen (mg L^{-1}) concentration Station 595 during the 2011 ice-free season, Lake Wolsey

In 2007, the bottom waters reached anoxic levels about a week earlier than 2008, however fall turnover occurred approximately 2 weeks later. In 2008, the bottom waters became anoxic by July 29th which is about 2 weeks earlier than 2009 or 2010; however fall turnover occurred later in 2008, which may explain the differences in the duration of anoxia. In 2009 and 2010, the bottom waters were anoxic by mid-August with fall turnover occurring later than 2009. In 2011, the anoxic period exceeded 60 days (Figure 33) and represents the longest anoxic period observed in the bottom waters of Lake Wolsey between 2007 – 2011. The onset of anoxia and the timing of fall turnover may explain the differences in the duration of anoxia between years and should be considered when examining temporal trends.

We used our dissolved oxygen and temperature with depth profile data to ground-truth these measurements. We found good correspondence between the profile data and the real-time *in situ* measurements of dissolved oxygen, under a broad range of conditions including oxic and anoxic conditions and across years (2007 – 2010) (Figure 36).

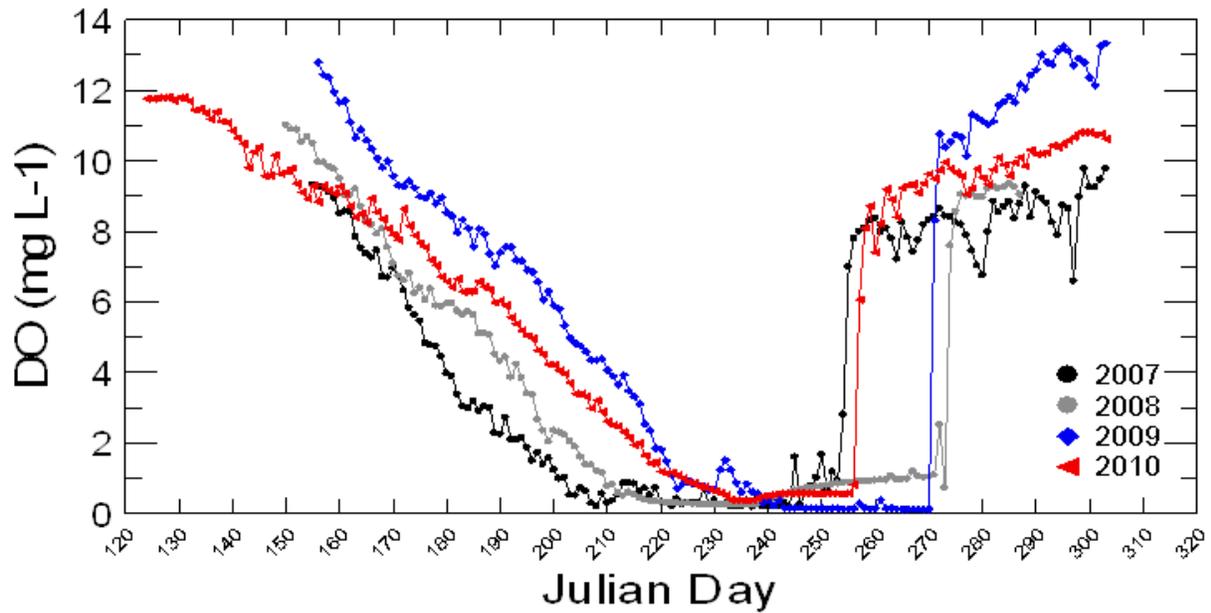


Figure 34 Bottom-water (21 - 22 m) dissolved oxygen (mg L^{-1}) concentrations at Station 595 during the ice-free season from 2007 to 2010, Lake Wolsey

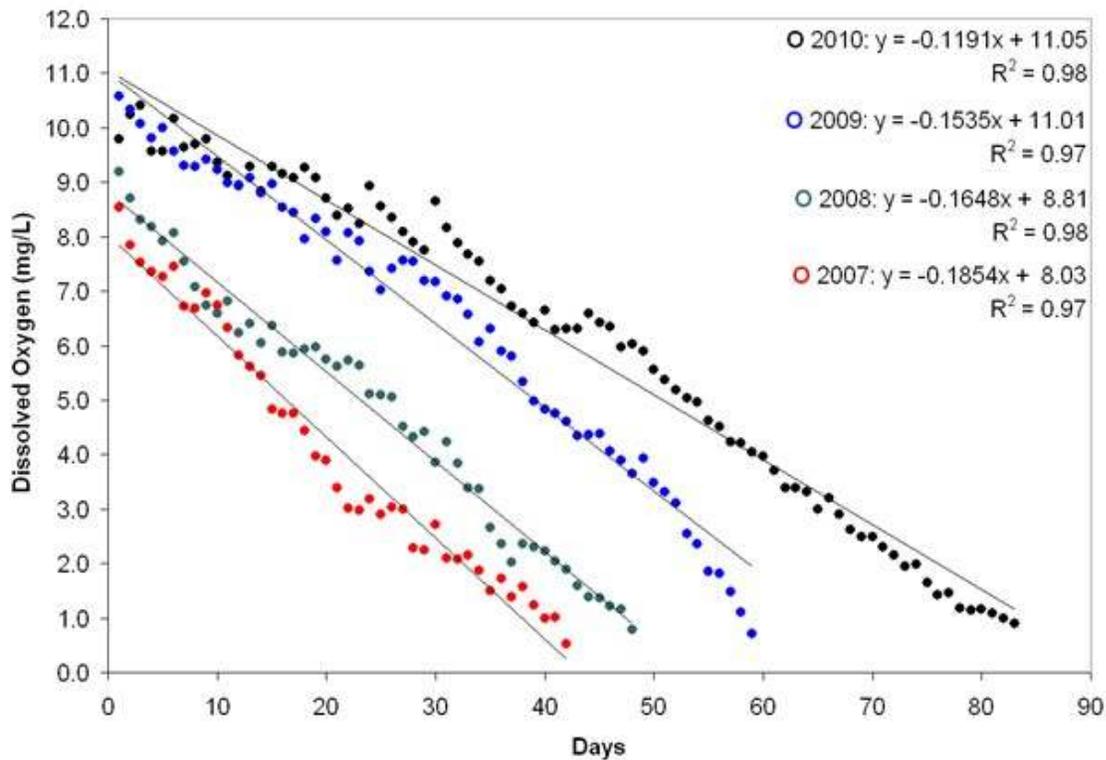


Figure 35 Dissolved oxygen depletion rates for real-time continuous sensors deployed in the bottom waters of Lake Wolsey (~ 22m), 2007 - 2010

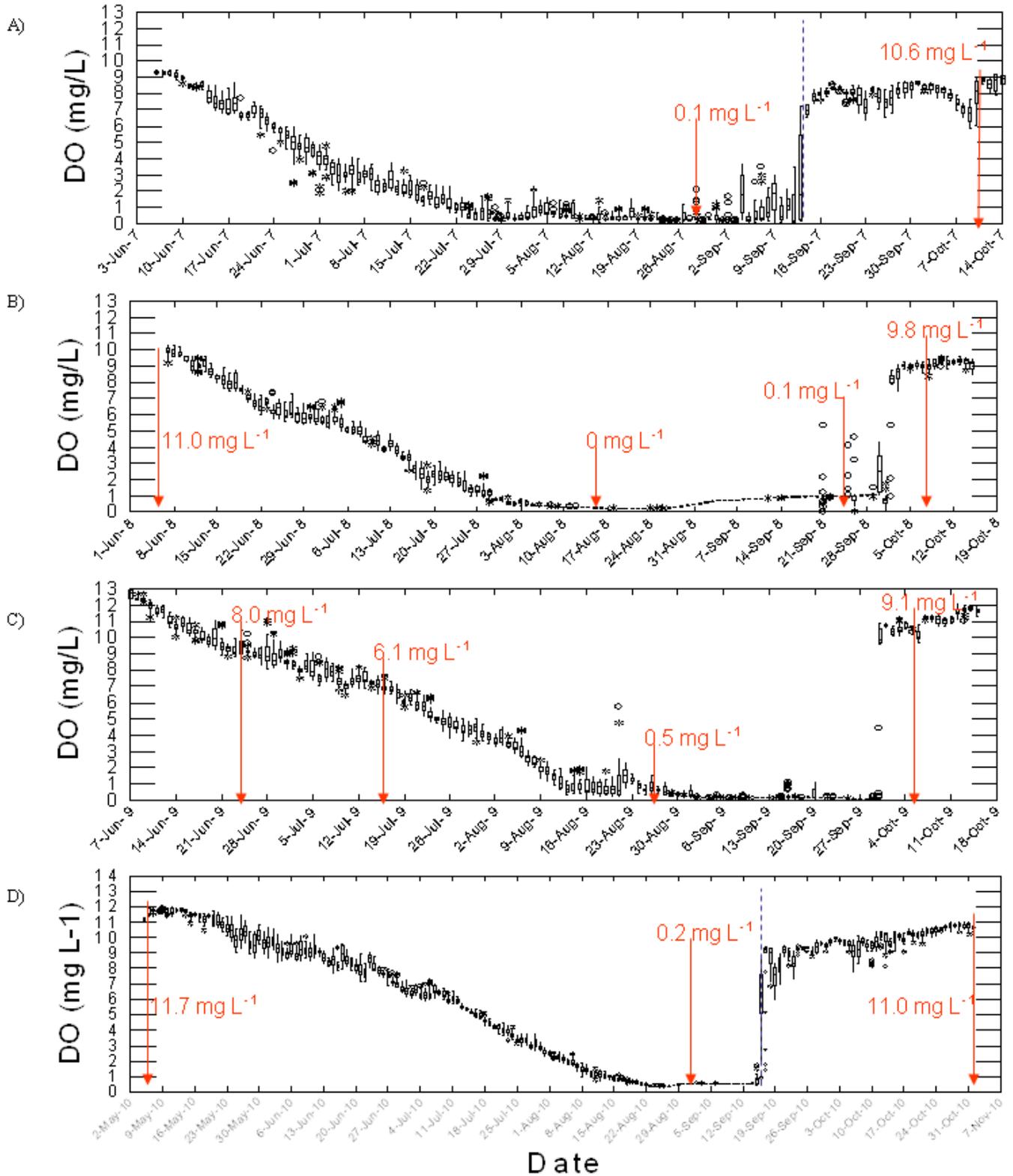


Figure 36 Dissolved oxygen concentration (mg L⁻¹) as a function of time in a) 2007 b) 2008 c) 2009 and d) 2010, Lake Wolsey

3.5.2 Dissolved Oxygen: Profiles and Volume-weight Averaged Concentrations

In the previous section we presented data from the *in situ* real-time continuous sensors to provide us with an understanding of the thermal dynamics of this embayment between 2007—2011. In addition to this data, we analyzed over 350 temperature profiles collected between 1986 to 2014 which provided good spatial and temporal data on the thermal structure of the Lake Wolsey both historically and more recently. We applied the same approach as the real-time continuous data analysis and determined water column characteristics using water density to determine stratification patterns and the boundary depths of the epilimnion, metalimnion and hypolimnion. Along with the 2006 bathymetry data, we calculated the volume-weight (VW) averaged temperature for the epilimnion, metalimnion and hypolimnion. The date was normalized to Julian Day to facilitate analysis of seasonal temperature trends and between year variability.

The average temperature in the surface mixed layer or epilimnion, of all stations was plotted against day (Figure 38) to differentiate seasonal patterns in surface water temperature conditions. The surface waters of Lake Wolsey followed a clear heating and cooling pattern with VW averaged temperature $< 10^{\circ}\text{C}$ in early spring and rapidly warm up in the summer (Figure 38). The surface waters of Lake Wolsey are generally warm and exceed 20°C by mid-summer. Although there is a strong positive relationship between epilimnetic and metalimnetic water temperature (Figure 37), the thermal properties of the hypolimnion exhibit high interannual variability. While water temperature is a factor when considering hypolimnetic dissolved oxygen depletion, the anoxia observed in recent years paradoxically corresponded to cooler hypolimnetic water temperatures.

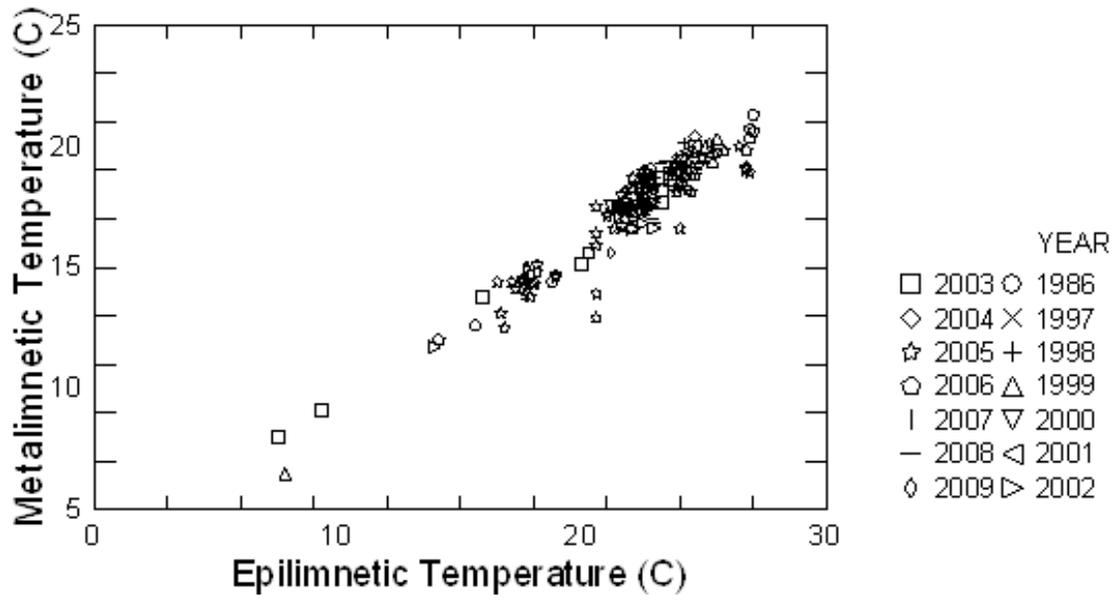


Figure 37 The relationship between volume-weighted epilimnetic and metalimnetic water temperature (°C) during the ice-free season from 1986 to 2009

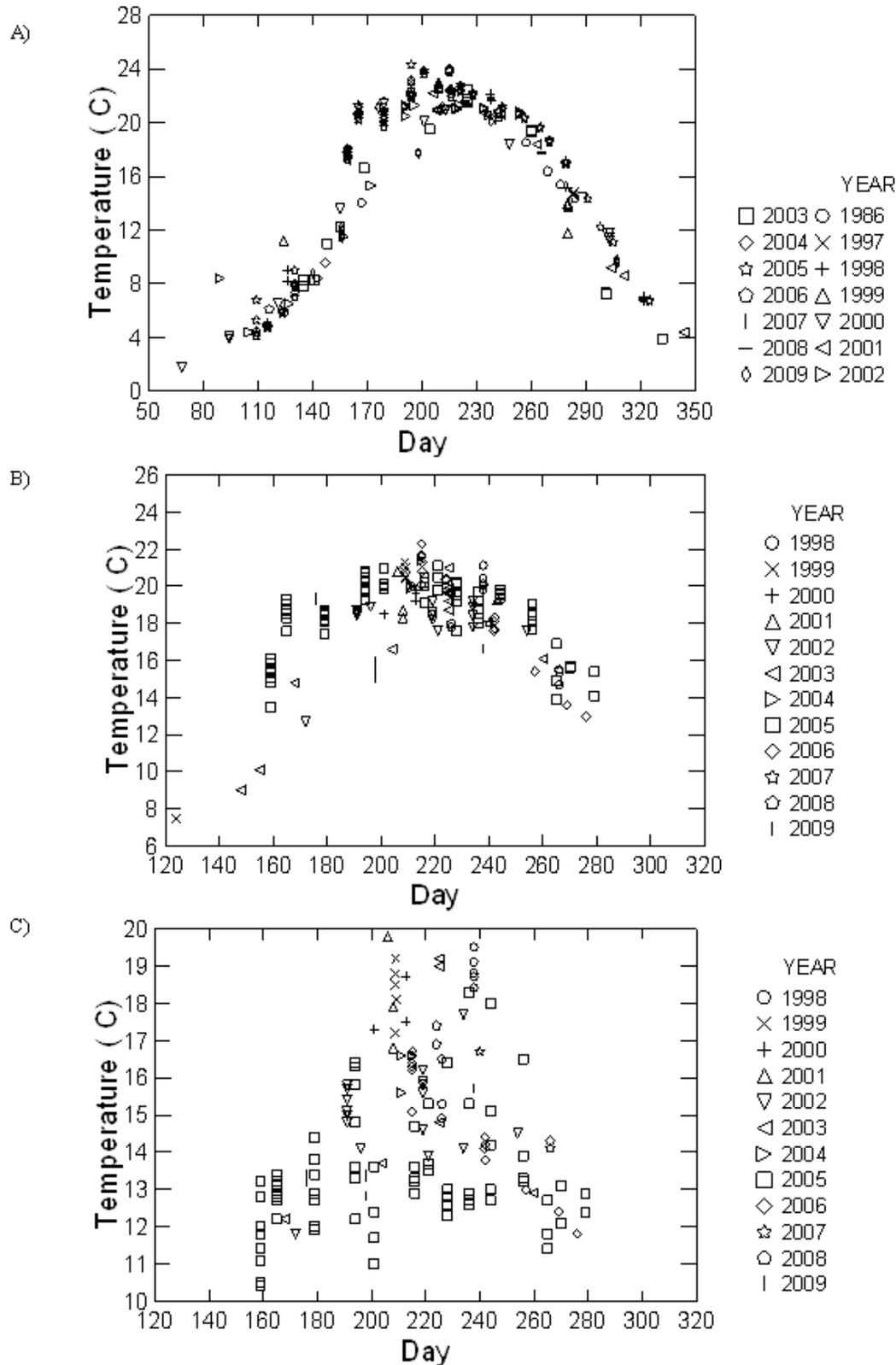


Figure 38 Volume-weighted average water temperature (°C) in the a) epilimnion b) metalimnion and c) hypolimnion during the ice-free season from 1986 to 2009, Lake Wolsey

Volume-weighted average metalimnetic temperature was also calculated and followed the same pattern as the epilimnetic layer with water temperature peaking between Day 200 to 220 (Figure 38). The metalimnion exhibited a similar trend, with VW averaged metalimnetic temperatures also approaching 20°C (Figure 38). The density difference between the epilimnion and metalimnion is comparatively smaller compared to the hypolimnion.

Since 2000 there appears to be a progressive decline in the minimum water temperature and the bottom waters were coolest in 2004/05 and more recent conditions (post-2005) indicate VW averaged hypolimnetic temperatures of less than 14°C.

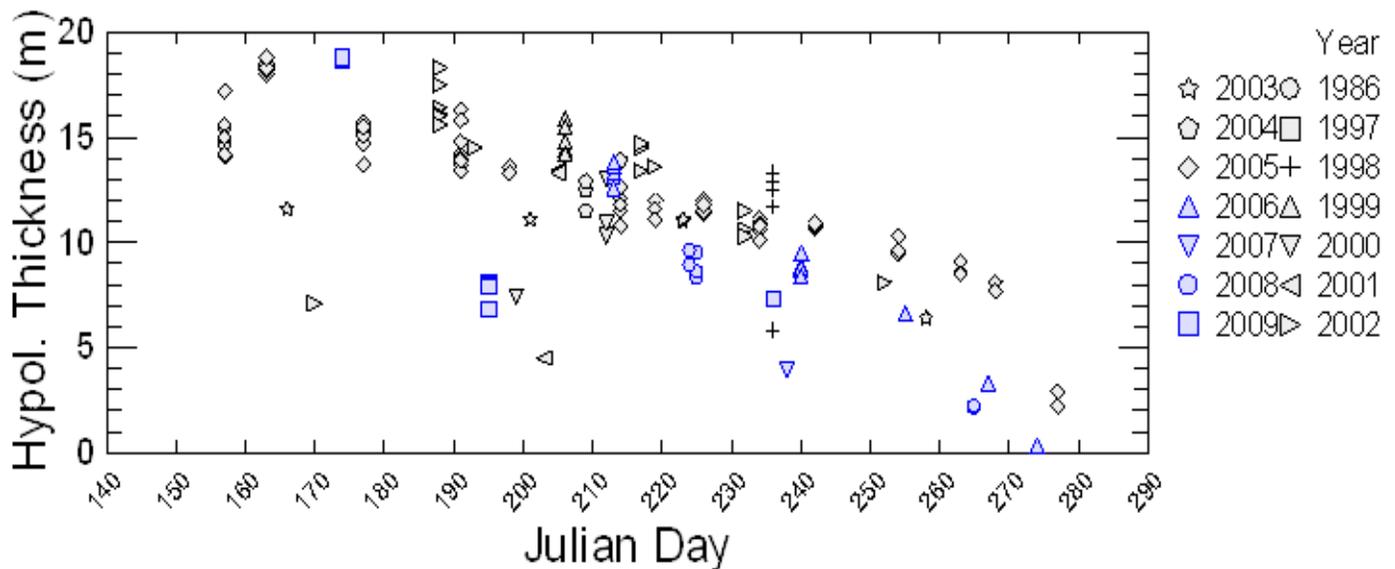


Figure 39 Hypolimnetic thickness (m) as a function of time (Julian Day) from 1986 to 2009, Lake Wolsey

We determined the hypolimnetic thickness for all deep stations across all years as plotted it as a function of Julian day to facilitate the through-time analysis (Figure 39). We found hypolimnetic thickness as large as 18 m in early spring with progressive decline in hypolimnetic thickness over the ice-free season. Charlton (1980) found waterbodies with thin or small hypolimnetic thickness to be more susceptible to DO depletion, however for our dataset, we found this embayment possessed a large hypolimnetic thickness ranging from 6 m to 10 m in late-summer.

3.5.3 Vertical Profiles: Dissolved Oxygen Data

Recent data have shown that the dissolved oxygen (DO) condition of this embayment is severely degraded with hypolimnetic anoxia occurring for an extended period during the summer stratified season, as evidenced by the real-time continuous DO data collected between 2007 – 2011. We analyzed recent and historical DO and temperature with depth profile data collected between 1986 to 2014 to better understand DO dynamics temporally and spatially. We used the volume-weighted average approach to estimate the average DO concentrations for the three water masses: the epilimnion, metalimnion and hypolimnion and this data was used to track changes in the DO condition over time. This is an integrated approach, averaging DO concentration over volume, therefore near-bed DO conditions are weighted less than DO conditions near the top of the hypolimnion.

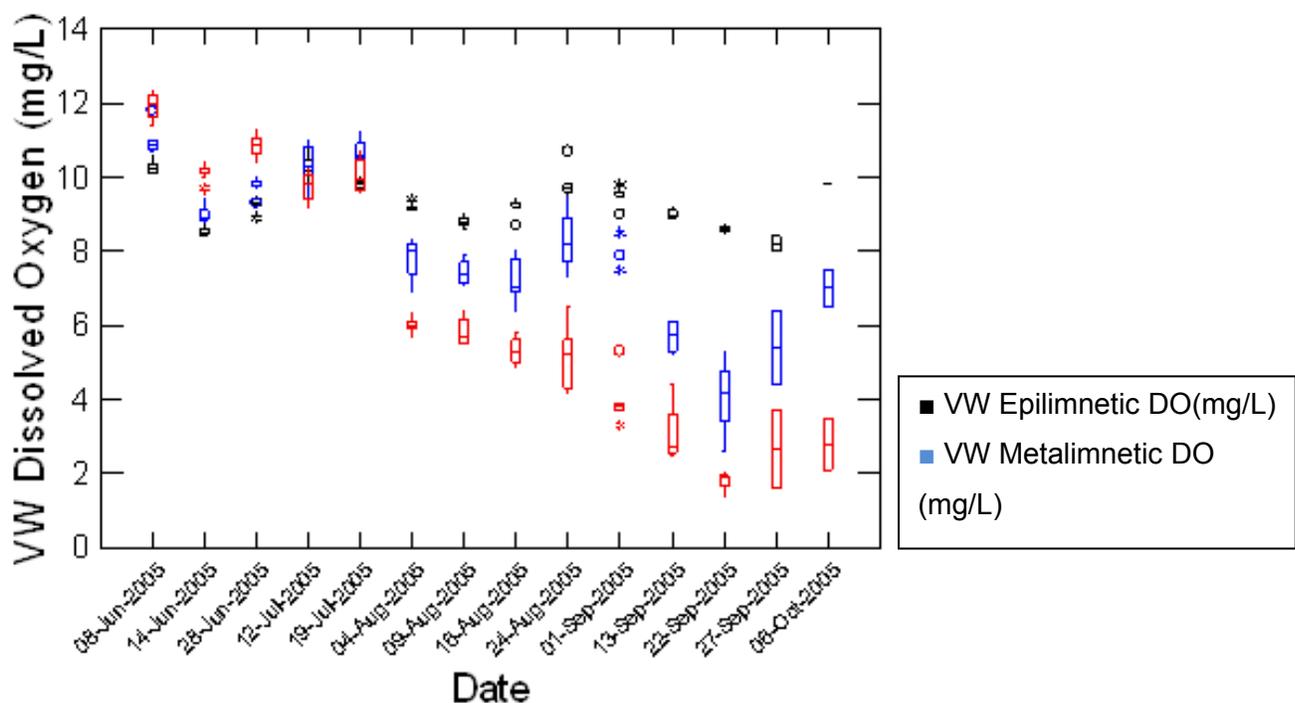


Figure 40 Volume-weighted epilimnetic, metalimnetic and hypolimnetic dissolved oxygen concentration (mg L^{-1}) 2005, Lake Wolsey

VW DO concentrations over time (Julian Day) clearly show distinct vertical patterns in the DO condition of this embayment corresponding to its water mass designation (e.g., epilimnion, metalimnion and hypolimnion) and this is best depicted based on 2005 data (Figure 42). In 2005, Lake Wolsey was intensively profiled to characterize the spatial and temporal

patterns in the dissolved oxygen and thermal regimes and this provided a unique opportunity to examine between station variability and seasonal patterns in dissolved oxygen condition. We found VW epilimnetic DO levels oscillated during the summer stratified season but were consistent between stations and were within 0.5 mg L^{-1} (Figure 40, Figure 41), which suggest these oscillation occurred lake-wide. The epilimnion remained well-oxygenated with VW epilimnetic DO concentrations above 8 mg L^{-1} throughout the ice-free season (Figure 40, Figure 41). Vertical differences were evident with divergence in DO condition by mid-summer between the three water masses. Although well-oxygenated in early summer declines in DO were evident in the metalimnion and hypolimnion over the stratified season. By late-summer VW hypolimnetic DO concentrations fell below 4 mg L^{-1} , but did not reach anoxic conditions (Figure 40).

When we examined the entire DO profile dataset and plotted VW epilimnetic DO concentration against day, we find that across all years the surface mixed waters or epilimnion were well oxygenated with volume-weighted average (VW) epilimnetic DO concentrations above 7 mg L^{-1} through the ice-free season and well above the Provincial Water Quality Objectives (PWQOs) of 6 mg L^{-1} for DO (Figure 42). As expected, VW epilimnetic DO concentrations were highest in the spring when temperatures were low and lowest during the summer when water temperatures were highest (Figure 42) and this is consistent with the real-time continuous *in situ* DO results.

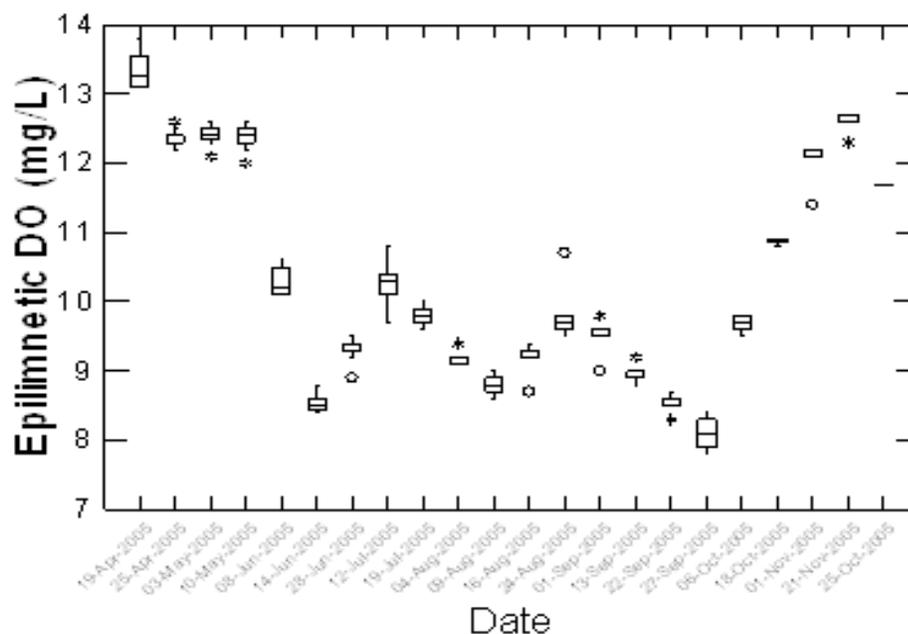


Figure 41 Volume-weighted average epilimnetic dissolved oxygen concentration (mg L^{-1}) of during the

ice-free season, stations sampled in 2005.

Metalimnetic waters exhibited a wide range in VW DO values with concentrations ranging from 0.6 mg L⁻¹ to 11.8 mg L⁻¹. The metalimnion was well-oxygenated in early-summer, however DO declined over the summer stratified season (Figure 43). It was not until 2003 that we observed metalimnetic hypoxia and VW DO fell below 4 mg L⁻¹. In subsequent years thereafter metalimnetic hypoxia was observed in this embayment. Severe metalimnetic DO depletion first occurred in 2007 when VW DO concentrations fell below 2 mg L⁻¹ and by 2008 VW metalimnetic DO concentrations were well below 1 mg L⁻¹ (Figure 43). These results are consistent with our observation that 2008 exhibited the one of most degraded hypolimnetic DO condition based on the real-time continuous *in situ* DO data with an extended anoxic period and high DO depletion rate. Severe metalimnetic DO depletion was observed again in 2011 (Figure 44). These results indicate anoxia extended beyond the hypolimnion and into the metalimnion.

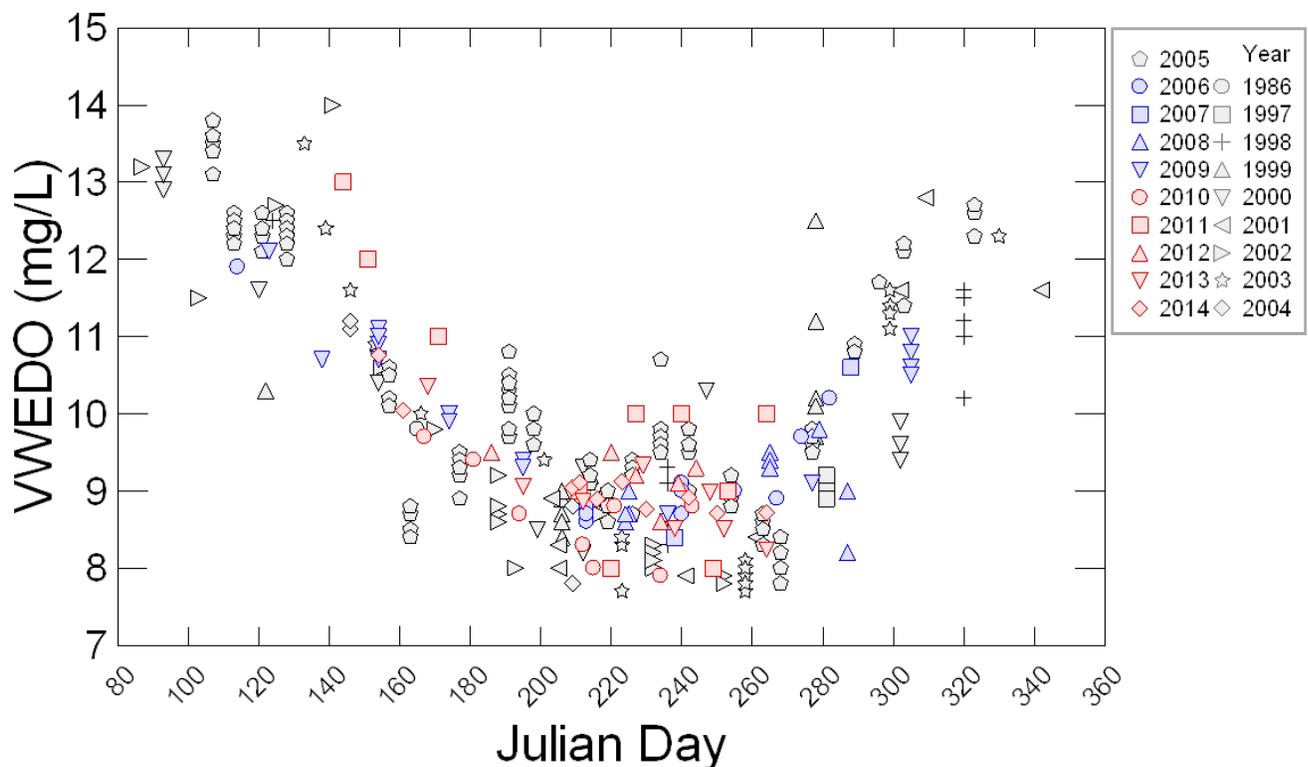


Figure 42 Volume-weighted average epilimnetic dissolved oxygen concentration (VWEDO) (mg L⁻¹) during the ice-free season from 1986 to 2014, Lake Wolsey

As with the metalimnion, VW hypolimnetic DO concentrations were highest in early summer and declined over the course of the summer stratified season with VW hypolimnetic levels ranging from < 0.1 mg L⁻¹ to 12.3 mg L⁻¹ (Figure 44). In early summer, the hypolimnion was well-

oxygenated with VW hypolimnetic dissolved oxygen concentrations above the PWQOs for dissolved oxygen (Figure 44). The hypolimnion became hypoxic by mid to late summer and VW hypolimnetic DO concentrations fell below 4 mg L⁻¹. Hypolimnetic anoxia with VWHDO concentrations below 2 mg L⁻¹ was observed in the mid-2000s and occurs regularly in Lake Wolsey and is indicative of seriously degraded conditions. Severe DO depletion in the entire hypolimnion remains an ongoing environmental issue and as recently as 2015, VWHDO fell well below 1 mg L⁻¹ in late summer (Figure 45).

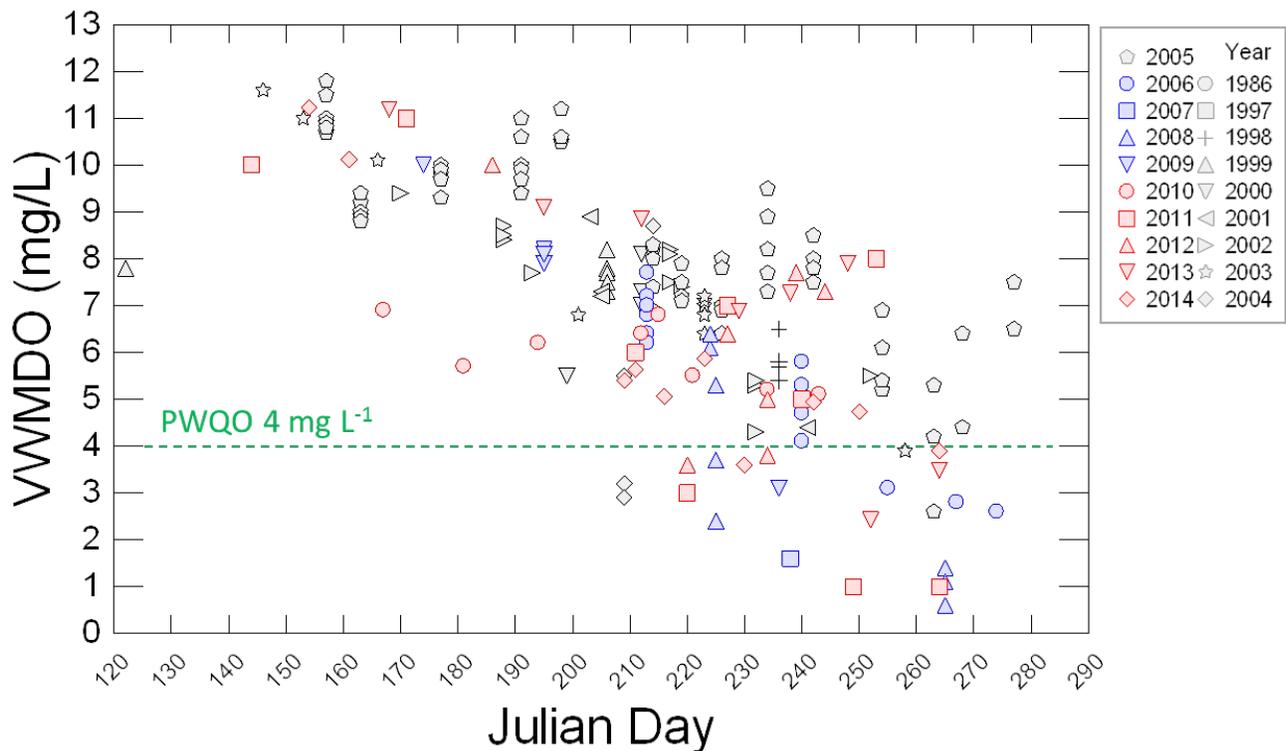


Figure 43 Volume-weighted average metalimnetic dissolved oxygen concentration (VWMDO) (mg L⁻¹) during the ice-free season from 1986 to 2014, Lake Wolsey

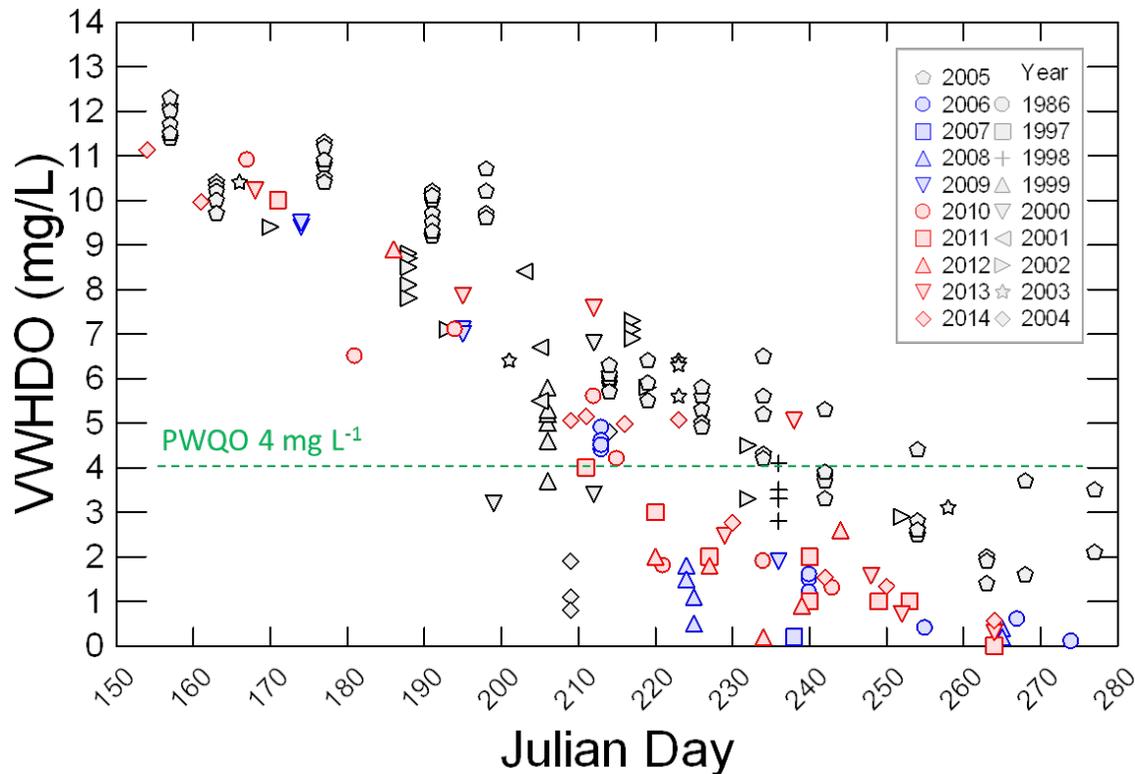


Figure 44 Volume-weighted average hypolimnetic dissolved oxygen concentration (VWHDO) (mg L^{-1}) during the ice-free season from 1986 to 2014, Lake Wolsey

VW hypolimnetic DO depletion rates were estimated using DO profile data with sufficient temporal resolution. VWHDO depletion rates were high and ranged from $0.074 \text{ mg L}^{-1} \text{ day}^{-1}$ to $0.134 \text{ mg L}^{-1} \text{ day}^{-1}$ (Figure 46). Between 2002 and 2006 VW hypolimnetic DO depletion rates were below $0.1 \text{ mg L}^{-1} \text{ day}^{-1}$. From 2009 to 2014, VWHDO depletion rates increased and were at or above $0.1 \text{ mg L}^{-1} \text{ day}^{-1}$ (Figure 46, Table 11). DO depletion rates using the integrated approach (VW DO) were similar to those estimated from discrete data (i.e., near-bottom DO concentration) in 2010 and were slightly lower in 2009 (Figure 35, Figure 46, Table 11).

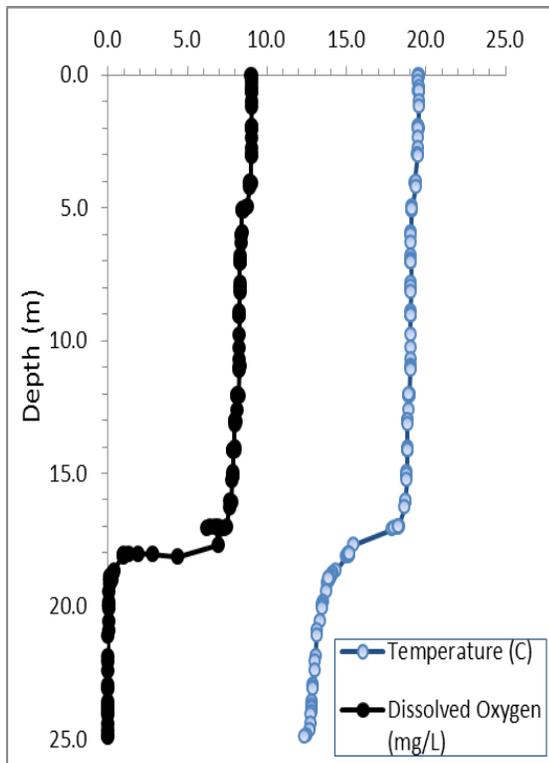


Figure 45 Dissolved oxygen (mg L^{-1}) and temperature ($^{\circ}\text{C}$) with depth profile taken in Lake Wolsey on September 15, 2015

To determine if temperature is a driving factor in the observed DO depletion in Lake Wolsey we examined the relationship between VW hypolimnetic temperature and VW hypolimnetic DO. We found there was a poor relationship between volume-weighted average hypolimnetic temperature and VW hypolimnetic DO (Figure 47) which suggests thermal warming is likely not a driving factor in the recent wide-spread hypolimnetic anoxia observed in this embayment. Interestingly, there was a significant relationship between VW metalimnetic DO and VW hypolimnetic DO (Figure 48).

VWHDO concentrations were also normalized to 4°C and plotted as a function of time to examine inter-annual trends in the DO condition (Figure 49). Temperature-normalized VWHDO concentrations exhibited the same pattern with well-oxygenated hypolimnia in early summer and DO depletion leading to hypolimnetic anoxia by mid to late summer (Figure 44, Figure 49).

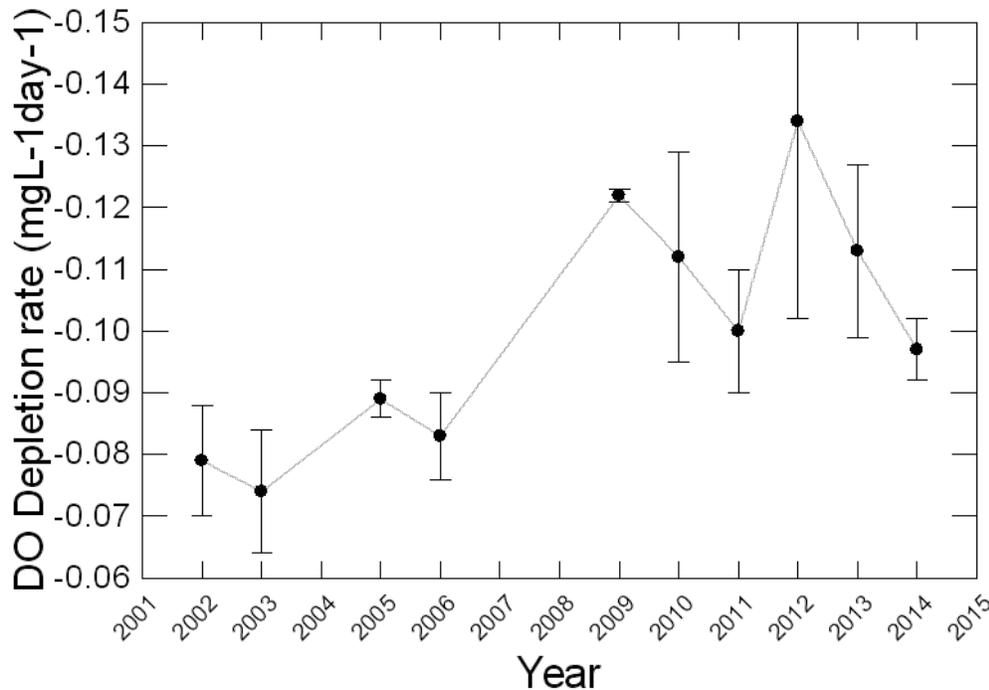


Figure 46 Volume-weighted average hypolimnetic dissolved oxygen concentration (VWHDO; mg L⁻¹) depletion rates between 2002 to 2014, Lake Wolsey

Table 11 Volume-weighted average hypolimnetic dissolved oxygen depletion rates (mg L⁻¹ day⁻¹; mg L⁻¹ month⁻¹) during the ice-free season from 1986 to 2014, Lake Wolsey

Year	Depletion Rate (mg L ⁻¹ day ⁻¹)	Depletion Rate (mg L ⁻¹ month ⁻¹)	Constant	N	Squared Multiple R	Standard Error	p-value
2002	-0.079	-2.41	23.2	17	0.823	0.009	< 0.05
2003	-0.074	-2.26	22.4	6	0.932	0.01	< 0.05
2005	-0.089	-2.71	25.9	70	0.918	0.003	< 0.05
2006	-0.083	-2.53	22.0	14	0.915	0.007	< 0.05
2009	-0.122	-3.72	30.7	10	0.999	0.001	< 0.05
2010	-0.112	-3.42	28.1	9	0.866	0.017	< 0.05
2011	-0.100	-3.05	25.9	10	0.927	0.01	< 0.05
2012	-0.134	-4.09	32.5	8	0.751	0.032	< 0.05
2013	-0.113	-3.45	29.6	10	0.885	0.014	< 0.05
2014	-0.097	-2.96	25.7	12	0.976	0.005	< 0.05

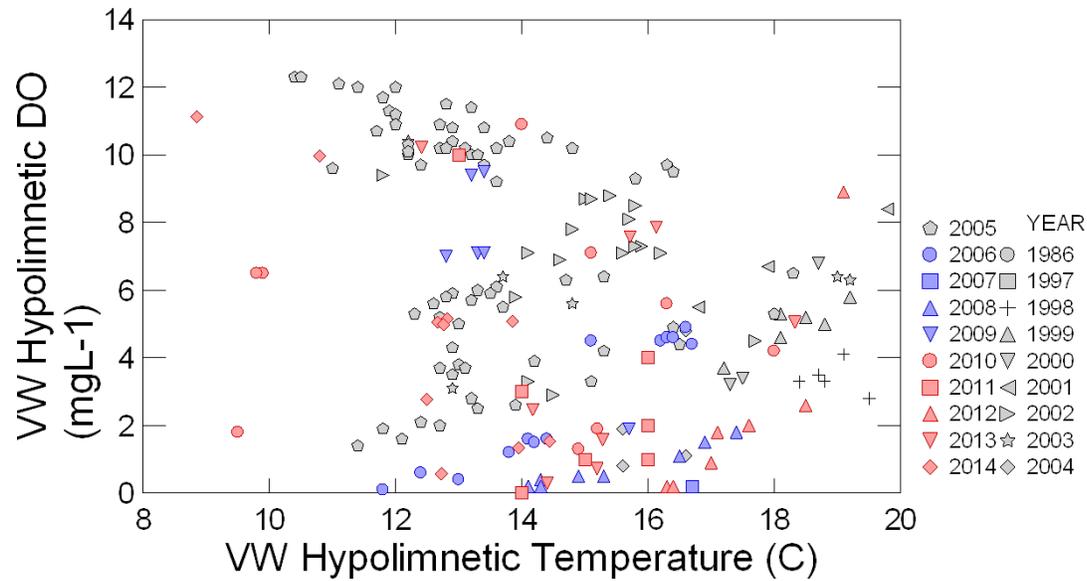


Figure 47 Relationship between volume-weighted averaged (VW) hypolimnetic dissolved oxygen (mg L^{-1}) and VW hypolimnetic temperature, 1986 - 2014, Lake Wolsey

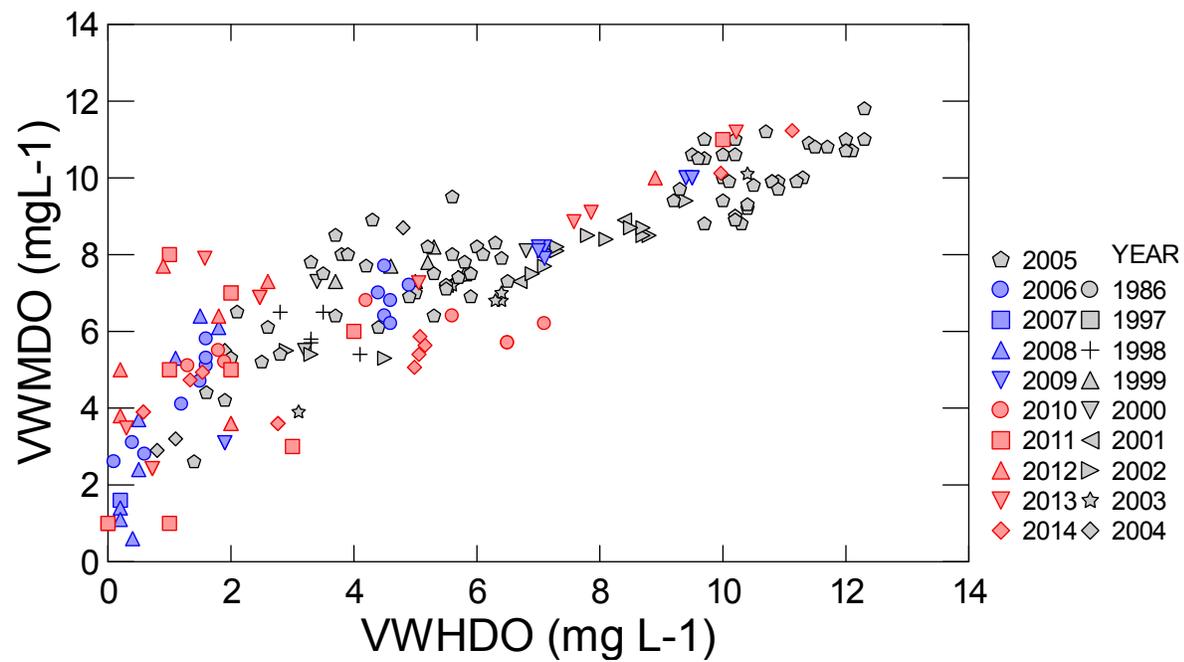


Figure 48 Relationship between volume-weighted average (VW) metalimnetic and VW hypolimnetic dissolved oxygen (mg L^{-1}), 1986 - 2014, Lake Wolsey

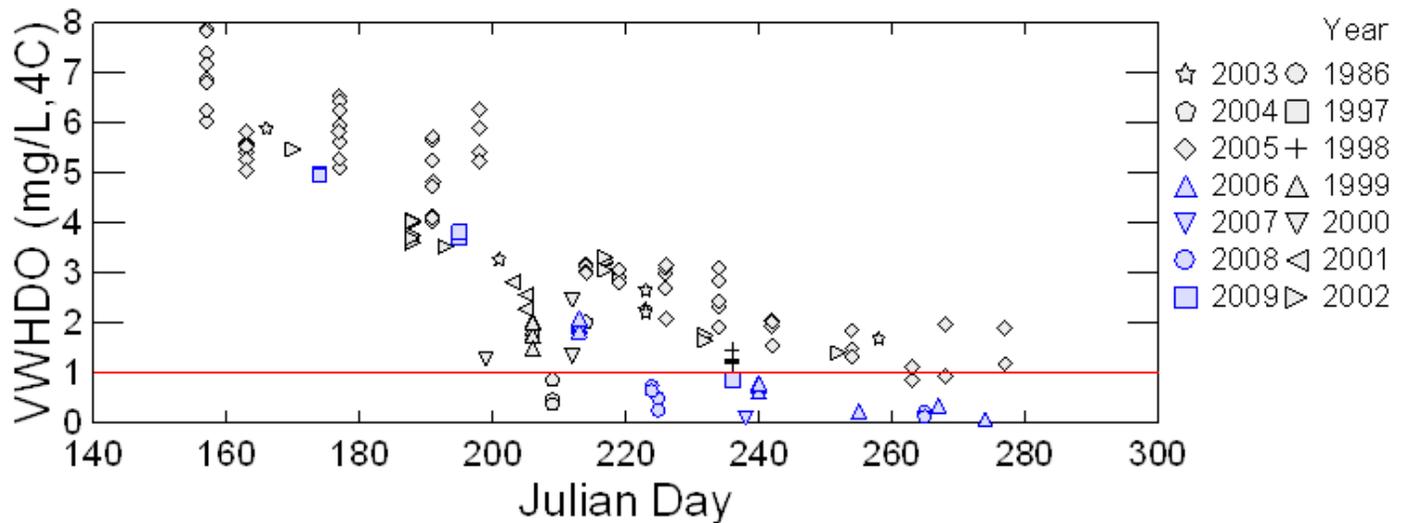


Figure 49 Volume-weight averaged hypolimnetic dissolved oxygen concentration (mg L^{-1}) normalized to 4°C as a function of time (Julian day), Lake Wolsey

The wide-spread hypolimnetic anoxia observed in Lake Wolsey is a regular occurrence, however the sediment surface area that is impacted depends on the thermal boundaries, stratification patterns and DO depletion rates. For example, in 2006, 2007 and 2008 the hypolimnetic anoxia was found to impact a sediment surface area of 593 ha, 382 ha and 861 ha or 29%, 19% and 42%, respectively. This broad range reflects the interannual variability we observed in the physical limnology of this system.

The real-time in situ DO data provided us with high resolution, within year accounting of the DO condition within this embayment, revealing a system with severe DO depletion that occurs rapidly and persists for significant proportion of the stratified season. The DO patterns from the profile data support these observations and show that this embayment is degraded with high DO depletion rates. Wide-spread hypolimnetic anoxia occurring since the mid-2000s, around the time harmful algal blooms were first observed in this system, and is now a chronic condition observed as recently as 2015.

3.5.4 DO Depletion Rates

Since the onset of anoxia varies between years, we estimated DO depletion rates based on the onset of stratification and when DO levels fall below 1 mg L^{-1} . From our analysis, DO depletion rates varied from 0.12 to 0.19 mg L^{-1} . Although 2008 experienced one of the longest anoxic period, DO depletion rates were highest in 2007 and, as expected, lowest for 2010. It is interesting to note that DO conditions at the onset of stratification varied between years. Initial DO levels were 8.6 mg L^{-1} , 9.9 mg L^{-1} , 10.7 mg L^{-1} and 11.1 mg L^{-1} for 2007, 2008, 2009 and 2010, respectively. Initial DO levels in 2007/08 were ~ 1 to 2 mg L^{-1} lower than 2009/10. The initial DO concentration at the onset of stratification is important because it is an important factor that determines the amount of DO available in the hypolimnion. For example, if we assume the hypolimnetic thickness is 8 m with a hypolimnetic volume $\sim 17\,900\,000\,000 \text{ m}^3$, the hypolimnion will possess $\sim 20\%$ less DO if the initial DO concentration is 9 mg L^{-1} when compared to a hypolimnion with initial DO concentration of 11 mg L^{-1} . If the top of the hypolimnion occurs at 14 m or 16 m , this results in a 2 to 4-fold increase in the amount of oxygen available when compared to 18 m .

The amount of DO available in the hypolimnion is not only a function of the initial DO conditions and timing of fall turnover, it is also a function of hypolimnetic thickness. The dissolved oxygen depletion rates for the bottom waters of Lake Wolsey ranged between $0.15 \text{ mg L}^{-1} \text{ day}^{-1}$ to $0.19 \text{ mg L}^{-1} \text{ day}^{-1}$ in 2007 – 2009. When this is normalized to month and temperature, the dissolved oxygen depletion was found to range between $2.4 \text{ mg L}^{-1} \text{ month}^{-1}$ to $2.9 \text{ mg L}^{-1} \text{ month}^{-1}$.

The real-time continuous *in situ* sensors provided high-resolution temporal data which allowed us to determine the duration and extent of the dissolved oxygen depletion. DO depletion occurred at all stations with hypolimnetic anoxia occurring by mid to late summer. Anoxic conditions persisted until either the thermocline exceeded station depth or until fall turnover.

Severe DO depletion is an annual and basin-wide occurrence in Lake Wolsey based on our 2007 – 2011 surveys. The waters of this embayment are well oxygenated with DO levels well above 6 mg L^{-1} in the spring and early summer and throughout the water column. As the summer stratified season progressed, there were distinct vertical differences in DO condition with severe DO depletion occurring in the bottom waters of Lake Wolsey. The hypolimnion occurred at all monitored stations and we found DO levels fell below 1 mg L^{-1} and the duration of this condition was found to vary between stations and years. Severe DO depletion is not only a near-bottom condition, but was found to extend up in the water column with anoxia and is

indicative of a wide-spread issue, spatially, temporally and vertically.

4 Conclusions

In this report we provide a summary of the available water quality data on Lake Wolsey from 1986 to 2014. This summary documents the degree to which the water quality of Lake Wolsey has deteriorated over time. We provide multiple lines of evidence including analysis of nutrient and water chemistry data, real-time *in situ* water quality data and dissolved oxygen and temperature profile data to characterize the physical and limnological conditions of this embayment and the degree of hypolimnetic (bottom-water) dissolved oxygen (DO) depletion.

Lake Wolsey is smaller and deeper than previously reported with a large littoral zone and a deep basin located in the southwest area of the embayment. It is a hydrologically dynamic system with fluctuating water levels, which can affect estimates of residence time, and hypolimnetic thickness. Water levels could fluctuate as much as 0.6 m. Hamblin & Gale (2002) found a 0.3 m water level had the potential to reduced average inflows from 14.5 to 9 m³ s⁻¹, thus increasing the residence time from 215 days to 294 days. A 0.3m drop in water level was found to increase the likelihood of severe dissolved oxygen depletion, leading to severe reductions in the chironomid population, while higher water levels were thought to facilitate the recovery of the chironomid community in Lake Wolsey (Clerk, 2001).

We found Lake Wolsey to be limnologically distinct from North Channel waters and more similar to the open-waters of the lower Great Lakes than the Precambrian shield lakes. Unlike the embayments located along the shores of the North Channel, Lake Wolsey was found to be an ionically rich, alkaline, hard-water waterbody, likely due to its dolomictic limestone watershed, these conditions were most notable in the spring. Declines in conductivity over the ice-free season suggest lower watershed influence and increasing Great Lakes influence on the water quality of this embayment. Sites proximal to the causeway exhibited comparatively lower conductivity, which suggest a higher open-lake influence. Chloride, a conservative tracer of anthropogenic influence, was generally low (~ 5 mg L⁻¹) and are indicative of low anthropogenic influence. Lake Wolsey is is a clear-water low-DOC embayment with an average DOC

concentration of 3 mg L^{-1} and an average secchi depth of 5 m. Particulate content is low with suspended solids concentrations of $\sim 1 \text{ mg L}^{-1}$ and turbidity values $< 1.5 \text{ FTU}$.

Lake Wolsey is a moderately productive mesotrophic embayment with phosphorus (P) levels varying seasonally in Lake Wolsey. Spring P conditions are typically low and $\leq 10 \text{ } \mu\text{g L}^{-1}$ and these P levels are consistent with levels that were observed historically and suggest that surface water P concentrations have not increased over time. However P levels increase to above the PWQO of $10 \text{ } \mu\text{g L}^{-1}$ in the summer and fall, which suggest additional, non-watershed based, inputs of nutrients over the ice-free season. Lake Wolsey is moderately productive with chlorophyll *a* levels below $5 \text{ } \mu\text{g L}^{-1}$. Although chlorophyll *a* and P levels would tend to suggest it is at low-risk for harmful algal blooms (HABs), since 2006 HABs regularly occur in this embayment despite chlorophyll *a* levels well below the threshold identified by Downing et al (2001). The real-time continuous chlorophyll *a* fluorescence data reveal multiple chlorophyll *a* peaks occurrences annually and this is consistent with the observation of multiple algal blooms in this embayment. The real-time continuous turbidity measurements followed the same temporal and spatial trend and we found there to be a stronger correlation between turbidity and chlorophyll *a* fluorescence at the deep sites, which suggest phytoplankton likely dominates the particulate pool at the deep site.

The limnological characteristics of the hypolimnion diverges from the epilimnion in mid to late summer and early fall, when the hypolimnion becomes progressively oxygen depleted. Hypolimnetic DO depletion resulted in limnologically distinct water masses with more nutrient-enriched conditions in the hypolimnion compared to the epilimnion suggestive of internal loading under anoxic conditions. Hypolimnetic P concentrations were generally similar to the mixed surface layer under oxic conditions, but were up to five-fold higher under anoxic conditions

The water column, as indicated by our *in situ* real-time continuous temperature sensors, underwent thermal stratification in early June with a well-oxygenated hypolimnion. By September density gradients diminish and fall turnover occurs in September/October in this embayment therefore duration of stratification is generally three to four long. Shallower sites generally experience shorter stratification periods, typically 10 to 24 days shorter, mostly due to deepening of the thermocline. This embayment is not thermally static, but fluctuates widely with varying hypolimnetic depths, likely, in part, as a function of water level patterns. The surface waters of Lake Wolsey are warm and water temperatures were found to exceed 20°C by mid-

summer however hypolimnetic waters remained cool ($\leq 16.0^{\circ}\text{C}$). There was no correlation between stratification length and DO depletion rates, likely because once the hypolimnion reached an anoxic state, it remained in that state until fall turnover. However, longer stratification periods resulted in greater number of anoxic days. The hypolimnetic boundary, though annually variable, is 12 to 16 m in mid to late summer and is indicative of a large hypolimnion with a hypolimnetic thickness ranging from 8 to 12 m.

Real-time *in situ* chlorophyll a and turbidity sensors reveal a highly variable climate. Multiple chlorophyll a peaks were observed during the ice-free season, typically in July and September/October, which suggest possible algal bloom occurrences. Data from our water quality sampling surveys did not coincide with the occurrence of the chlorophyll a or turbidity peaks, however algal blooms were observed in early fall of 2010 and 2011. There was good correspondence between the *in situ* chlorophyll a data and turbidity data for the deep site (Stn 595) and north site (Stn 598), which suggest phytoplankton likely constituted a large proportion of the particulate pool. There was poorer correspondence at the shallower near-cage site (Stn 596) which suggests contributions of non-algal particulates to water turbidity. The *in situ* conductivity results are consistent with our water quality survey information and reveal similar seasonal conductivity patterns. Conductivity values were high in the spring, evidence of watershed influence, and declined over the ice-free season, indicating declining watershed influence and increasing lake influence on the water quality of this embayment. Sites near the causeway and proximal to Campbell Bay, thus more influenced by North Channel / Great Lakes water, exhibited lower conductivity comparatively to the distal south sites.

We used DO and temperature profiles to characterize the thermal and DO characteristics of the Lake Wolsey water column from 1986 to 2014 using the volume-weighted average (VW) approach. As expected the surface waters of this embayment followed a clear warming and cooling cycle. VW epilimnetic or surface water temperature exceeded 20°C by mid-summer, however interannual variability was evident with maximum VW water temperatures 2005 and conditions to be coolest in 2009. VW metalimnetic temperatures were strongly correlated with VW epilimnetic temperatures and we found conditions in the metalimnion were warm with VW water temperatures approaching 20°C . The hypolimnion exhibited high interannual variability with a wide range in hypolimnetic thickness observed in this embayment and this is consistent with the *in situ* real-time continuous temperature data.

An evaluation of the current and historical temperature and dissolved oxygen profile data indicate that changes in the DO condition have occurred over time, with progressively more severe hypolimnetic DO depletion leading to anoxia in the mid-2000s. Although the epilimnion remains well-oxygenated throughout the ice-free season, volume-weighted average estimates during the stratified season reveal severe DO depletion occurring in the hypolimnion and metalimnion. Metalimnetic DO conditions were found to range widely between years with generally high VW DO concentrations in early summer, which declined over the summer stratified season. Metalimnetic hypoxia, ($< 4 \text{ mg L}^{-1}$) first occurred in 2003 and the years thereafter. We first observed metalimnetic anoxia ($< 1 \text{ mg L}^{-1}$) in 2008 which indicate severely degraded water quality conditions. Unlike the VW temperature determinations, we found VW metalimnetic DO concentrations were strongly correlated to VW hypolimnetic DO concentrations.

As with the real-time *in situ* data, we found the hypolimnion to be well-oxygenated in early-summer and hypolimnetic DO depletion occurred with progressive depletion of oxygen over the summer stratified season and was observed in across years. Hypolimnetic hypoxia typically occurred in mid to late summer with VWHDO falling below 4 mg L^{-1} . This embayment historically experienced hypolimnetic hypoxia with near-bed anoxia since 1999, however wide-spread anoxia, a condition where there is absence or near-absence of dissolved oxygen in the entire hypolimnion, is a recent phenomenon. Hypolimnetic anoxia was observed from 2006 to 2014 and critically low DO concentrations ($< 2 \text{ mg L}^{-1}$) potentially impacted a large sediment surface area, however the extent varied by year. VWHDO depletion rates are high in this system and recent conditions (2009 – 2014) indicates rates are $\geq 0.10 \text{ mg L}^{-2} \text{ day}^{-1}$. DO conditions were tracked continuously during the ice-free season between 2007 to 2011 and support the findings that severe hypolimnetic and metalimnetic DO depletion occurs in Lake Wolsey. The rate of DO depletion varies from year to year, however in all years anoxic conditions occur by mid to late summer and remain anoxic until fall turnover or when the thermocline exceeds site depth. Hypoxia and anoxia occurs for a significant proportion of the summer stratified season.

This report provides a summary analysis of the available water quality data on Lake Wolsey, both historically and recently. Based on this analysis we conclude that the water quality condition of this clear-water moderately productive embayment water quality condition has deteriorated with occurrences of HABs and wide-spread hypolimnetic anoxia since the mid-

2000s. Although some hypolimnetic DO depletion is expected, severe hypolimnetic DO depletion resulting in the absence or near-absence of oxygen in the entire extent of the hypolimnion, persisting for a significant portion of the summer stratified season, is a recent phenomenon which is of concern. Although traditional eutrophication metrics (spring TP, chlorophyll, water clarity) suggest a low-risk for eutrophication effects, this analysis highlights the uniqueness of this embayment since these metrics fail to predict the occurrence and extent of eutrophication effects such as HABs and chronic hypolimnetic anoxia. Further studies examining the susceptibility of this embayment to wide-spread hypolimnetic anoxia will likely require an understanding of its physical limnology and the allochthonous and anthropogenic inputs to this embayment.

5 References

Boyd, D., M. Wilson, and T. Howell. 2001. Recommendations for Operational Water Quality Monitoring at Cage Culture Aquaculture Operations. Ontario Ministry of the Environment.

Canadian Council of Ministers of the Environment. 1999. Canadian water quality guidelines for the protection of aquatic life: Dissolved oxygen (freshwater). In Canadian environmental quality guidelines, 1999, Canadian Council of Ministers of the Environment, Winnipeg.

Canadian Council of Ministers of the Environment. 2004. Canadian water quality guidelines for the protection of aquatic life: Phosphorus: Canadian Guidance Framework for the Management of Freshwater Systems. In: Canadian environmental quality guidelines, 2004, Canadian Council of Ministers of the Environment, Winnipeg.

Charlton M.N. 1980. Hypolimnion Oxygen Consumption in Lakes: Discussion of Productivity and Morphometry Effects. *Can. J. Fish. Aquat. Sci.* 37: 1531 - 1539

Clerk, S., 2001. Master of Science Thesis: Fossil chironomids as indicators of water quality impacts from aquaculture activities. Queen's University, Kingston, Ontario.

Cooke S.E. and E.E. Prepas. 1998. Stream phosphorus and nitrogen export from agricultural and forested watersheds on the Boreal Plain. *Can. J. Fish. Aquat. Sci.* 55: 2292 - 2299.

Coote D.R. and F.R. Hore. 1978. Pollution Potential of Cattle Feedlots and Manure Storages in the Canadian Great Lakes Basin. Agricultural Watershed Studies Project 21 - Final Report

Diep N., T. Howell, N. Benoit and D. Boyd. 2007. Limnological Conditions of Eastern Georgian

Bay: Data Summary of the 2003 – 2005 Water Quality Survey. Ontario Ministry of Environment

Downing J.A., S.B. Watson and E. McCauley. 2001. Predicting Cyanobacteria dominance in lakes. *Can. J. Fish. Aquat. Sci.* 58: 1905 - 1908

Gale P. 1999. Lake Wolsey, 1999 Water Quality. Technical Memorandum to Brian McMahon. Ontario Ministry of Environment.

Giani A., D.F. Bird, Y.T. Prairie and J.F. Lawrence. 2005. Empirical study of cyanobacterial toxicity along trophic gradient of lakes. *Can. J. Fish. Aquat. Sci.* 62: 2100 - 2109

Hamblin P.F. and P. Gale. 2002. Water Quality Modeling of Caged Aquaculture Impacts in Lake Wolsey, North Channel of Lake Huron. *J. Great Lakes Res.* 28(1):32 - 43.

Health Canada. 2002. Cyanobacterial Toxins — Microcystin-LR.
<http://healthycanadians.gc.ca/publications/healthy-living-vie-saine/water-cyanobacteria-cyanobacterie-eau/alt/water-cyanobacteria-cyanobacterie-eau-eng.pdf>

Hecky R.E., R.E.H. Smith, D.R. Barton, S. J. Guildford, W.D. Taylor, M.N. Charlton, and T. Howell. 2004. The nearshore phosphorus shunt: a consequence of ecosystem engineering by dreissenids in the Laurentian Great Lakes. *Can. J. Fish. Aquat. Sci.* 61: 1285 – 1293

Hoffman D.W., R.E. Wicklund, and N.R. Richards. 1959. Soil Survey of Manitoulin Island Ontario. Report No. 26 of the Ontario Soil Survey. Canada Department of Agriculture, Ottawa.

Hille K.A. 2008. Does Aquaculture Impact Benthic Algal Ecology? A study on the effects of an experimental cage aquaculture operation on epilithic biofilms. Master of Science Thesis University of Manitoba, Winnipeg.

Meding M.E. and L.J. Jackson. 2003. Biotic, chemical, and morphometric factors contributing to winter anoxia in prairie lakes. *Limnol. Oceanogr.* 48(4): 1633 - 1642.

Merilainen J.J., J. Hynynen, A. Palomaki, P. Reinikainen, A. Teppo, and K. Granberg. 2000. Importance of diffuse nutrient loading and lake level changes to the eutrophication of an originally oligotrophic boreal lake: a palaeolimnological diatom and chironomid analysis. *Journal of Paleolimnology* 24(3): 251-270.

Milne, J. 2009. Presentation: Nutrient Mass Balance Modeling on a Freshwater Lake with Cage-aquaculture on Manitoulin Island, Ontario, Canada. Freshwater Forum, Sudbury, Ontario.
www.ontarioaquaculture.com/forum_II_final/presentations/presentation_j_milne.pdf

Milne J.E., C.H. Marvin, R. Yerubandi, K. McCann and R.D. Moccia. 2015. Monitoring and modelling total phosphorus contributions to a freshwater lake with cage-aquaculture. *Aquaculture Research* 1-15

NAR, 2010. Meeker's Aquaculture - 2009 Water Quality Monitoring Report. Report from N.A.R. Environmental Consultants Inc dated February 25, 2011

NAR, 2011. 2010 Annual Water Quality Monitoring Report for Meeker's Aquaculture. Report from N.A.R. Environmental Consultants Inc dated February 24, 2012

NAR, 2012. 2011 Annual Water Quality Monitoring Report for Meeker's Aquaculture. Report from N.A.R. Environmental Consultants Inc dated February 28, 2013

NAR, 2013. 2012 Meeker's Aquaculture – Water Quality Monitoring Report. Report from N.A.R. Environmental Consultants Inc dated February 28, 2014

NAR, 2014. 2013 Meeker's Aquaculture – Water Quality Monitoring Report. Report from N.A.R. Environmental Consultants Inc dated February 24, 2014

NAR, 2015. 2014 Meeker's Aquaculture – Water Quality Monitoring Report. Report from N.A.R. Environmental Consultants Inc dated February 10, 2015

Nürnberg G.K. 1996. Trophic State of Clear and Colored, Soft- and Hardwater Lakes with Special Consideration of Nutrients, Anoxia, Phytoplankton and Fish. *Lake and Reservoir Management* 12(4): 432-447, DOI: 10.1080/07438149609354283

Ontario Ministry of Environment (MOE). 1993. Guidelines for the Protection and Management of Aquatic Sediment Quality in Ontario. Ontario Ministry of Environment and Energy, Toronto, Ontario MOE, 1994. Water Management, Policies, Guidelines, Provincial Water Quality Objectives. Ontario Ministry of Environment and Energy, Toronto, Ontario

Ontario Ministry of Environment (MOE). 1994. Water Management – Policies, Guidelines, Provincial Water Quality Objectives. Ontario Ministry of Environment and Energy.

Ontario Ministry of the Environment (MOE). 1999. Water Quality Conditions Surrounding Aquaculture Cage Operations in the North Channel, Lake Huron and Depot Harbour, Georgian Bay. Technical Memorandum from P.Gale to B.McMahon dated August 19, 1999.

Ontario Ministry of the Environment (MOE). 2006a. Identification of surface water algae samples

from Wolsey Lake, Manitoulin Island taken Sept 14 and Oct 3, 2006. Technical Memorandum from L. Nakamoto to R. Sein dated Oct 17, 2006.

Ontario Ministry of Environment (MOE). 2006b. Technical Support Document for Ontario Drinking Water Standards, Objectives and Guidelines. Ontario Ministry of Environment, PIBS 4449e01

Prairie Y. T., D.F. Bird, and J.J. Cole. 2002. The summer metabolic balance in the epilimnion of southeaster Quebec lakes. *Limnol. Oceanogr.* 47(1): 316 - 321.

Quinlan R., A.M. Paterson, J.P. Smol, M.S.V. Douglas and B.J. Clark. 2010. Comparing different methods of calculating volume-weighted hypolimnetic oxygen (VWHO) in lakes. *Aquat. Sci.* 67: 97 - 103

Van Geest J. and M. Nowierski. 2007. Laboratory Sediment Toxicity Tests: Report on Aquaculture Cage Sediments in the North Channel of Georgian Bay, Manitoulin Island: Eagle Rock, Lake Wolsey and LaCloche Channel 2004. Ontario Ministry of Environment Technical Memorandum.

World Health Organization (WHO). 2006. Guidelines for drinking-water quality, third edition, incorporating first addendum. World Health Organization

Yan N.D. 2005. Research needs for the management of water quality issues, particularly phosphorus and oxygen concentrations, related to salmonid cage aquaculture in Canadian freshwaters. *Environ. Rev.* 13:1 - 19.

6 APPENDICES

APPENDIX 1 Summary of epilimnetic nutrient and chlorophyll a concentrations, Lake Wolsey (2008 - 2010)

Survey	Station	Water Depth (m)	Total Phosphorus (Dorset; µg L ⁻¹)	Total Phosphorus (LaSB; µg L ⁻¹)	Phosphate (mg L ⁻¹)	Total Kjeldahl Nitrogen (mg L ⁻¹)	Nitrite (mg L ⁻¹)	Nitrate (mg L ⁻¹)	Total Ammonium (mg L ⁻¹)	Chlorophyll a (µg L ⁻¹)	Chlorophyll b (µg L ⁻¹)
2008											
29-May-08	596	19.1	10.3	10.0	0.0005 ^W	0.335	0.001 ^W	0.005 ^W	0.0125	4.0	0.1 ^W
	595	23.5	10.8	10.5	0.0005 ^W	0.285	0.001 ^W	0.005 ^W	0.0060	4.3	0.1 ^W
12-Aug-08	596	18.1	17.0	13.0	0.0009 ^T	0.345	0.004 ^T	0.005 ^W	0.0045 ^T	3.9	0.1 ^W
	595	22.5	14.0	11.5	0.0012 ^W	0.315	0.006 ^W	0.005 ^W	0.0035	3.0	0.1 ^W
15-Oct-08	595	22.5	19.8	16.5	0.0117	0.280	0.001 ^W	0.005 ^W	0.0020 ^W	4.2	0.1 ^W
	596	18.8	19.7	17.5	0.0054 ^W	0.290	0.001 ^W	0.005 ^W	0.0020	3.3	0.1 ^W
2009											
05-Jun-09	596	18.6	7.3	11.0	0.0005 ^W	0.245	0.002 ^T	0.010 ^W	0.0185	1.4	0.1 ^W
	595	22.8	7.5	5.0 ^T	0.0005 ^W	0.205	0.001 ^W	0.010 ^W	0.0165	1.4	0.2 ^T
	235	12.9	6.6	8.0 ^T	0.0005 ^W	0.230	0.002 ^T	0.010 ^W	0.0220	1.1	0.2 ^T
	236	22.6	7.1	5.0 ^T	0.0005 ^W	0.200	0.002 ^T	0.010 ^W	0.0175	1.4	0.1 ^W
	237	19.9	6.6	5.0 ^T	0.0005 ^W	0.200	0.002 ^T	0.010 ^W	0.0165	1.3	0.1 ^W
	238	14.9	6.6	5.0	0.0005 ^W	0.210	0.001 ^W	0.011 ^W	0.0160	1.3	0.1 ^W
16-Jul-09	596	19.4	12.4	9.5	0.0005 ^W	0.260	0.001 ^W	0.010 ^W	0.0155	4.1	0.2 ^T
	595	23.2	13.8	10.5 ^T	0.0005 ^W	0.260	0.001 ^W	0.010 ^W	0.0150	4.2	0.2 ^W
	236	22.9	13.1	9.5 ^T	0.0007 ^T	0.245	0.001 ^W	0.010 ^W	0.0140	4.3	0.2 ^W
	235	13.2	11.7	10.5	0.0007 ^T	0.245	0.001 ^W	0.010 ^W	0.0180	4.2	0.2 ^T
	237	20.2	12.0	12.0	0.0006 ^T	0.260	0.001 ^W	0.010 ^W	0.0150	4.4	0.2 ^T
	238	15.1	11.3	10.0	0.0008 ^T	0.235	0.002 ^T	0.010 ^W	0.0150	4.3	0.2 ^T
03-Nov-09	238	15.1	12.1	11.5 ^T	0.0020 ^T	0.255	0.002 ^T	0.010 ^W	0.0150	3.7	0.1 ^W
	237	20.4	11.9	9.0 ^T	0.0020 ^T	0.255	0.003 ^T	0.010 ^W	0.0115	3.7	0.1 ^W
	235	12.9	12.6	10.5	0.0020 ^T	0.240	0.002 ^T	0.010 ^W	0.0130	4.2	0.1 ^W
	236	23.0	13.4	10.5	0.0018 ^T	0.240	0.002 ^T	0.010 ^W	0.0130	4.7	0.2 ^T
	595	23.0	11.8	10.0	0.0022 ^T	0.240	0.003 ^T	0.010 ^W	0.0115	4.6	0.2 ^T
	596	19.2	12.3	12.0	0.0019 ^T	0.255	0.002 ^T	0.010 ^W	0.0140	4.4	0.2 ^T
2010											
05-May-10	595	22.7	6.9	7.0 ^T	0.0019 ^T	0.230	0.003 ^T	0.357	0.0180	1.9	0.1 ^W
	596	18.9	5.9	4.0 ^T	0.0019 ^T	0.215	0.003 ^T	0.357	0.0190	1.8	0.1 ^W
	229	16.9	5.2	3.0 ^T	0.0018 ^T	0.220	0.003 ^T	0.357	0.0225	1.9	0.1 ^W
	235	13.0	8.1	2.5 ^T	0.0014 ^T	0.225	0.003 ^T	0.353	0.0325	1.8	0.1 ^W
	236	22.7	6.1	3.0 ^T	0.0014 ^T	0.225	0.003 ^T	0.356 ^W	0.0160	1.8	0.1 ^W
	598	19.9	5.0	6.0 ^T	0.0014 ^T	0.220	0.003 ^T	0.354	0.0190	1.8	0.1 ^W
	237	20.0	4.4	2.5 ^T	0.0015 ^T	0.225	0.003 ^T	0.356	0.0325	1.6	0.1 ^W
31-Aug-10	238	15.0	5.1	2.0 ^W	0.0015 ^T	0.215	0.003 ^T	0.356	0.0175	1.3	0.1 ^W
	596	18.4	13.1	7.5 ^T	0.0026 ^T	0.310	0.002 ^T	0.019 ^T	0.0290	3.9	0.1 ^W
	595	23.2	12.0	8.0 ^T	0.0025 ^T	0.275	0.002 ^T	0.021 ^T	0.0300	4.0	0.1 ^W
	236	22.7	12.9	9.0	0.0020 ^W	0.285	0.002 ^W	0.037 ^W	0.0235	4.4	0.1 ^W
	235	12.7	12.5	9.0 ^T	0.0017 ^T	0.260	0.002 ^T	0.021 ^T	0.0235	4.4	0.1 ^W
	229	17.3	13.0	7.5 ^T	0.0016 ^T	0.260	0.002 ^T	0.021 ^T	0.0285	4.3	0.1 ^W
01-Sep-10	237	19.8	13.3	10.0	0.0021 ^T	0.270	0.001 ^W	0.028 ^T	0.0225	4.7	0.1 ^W
	238	15.0	13.1	10.0	0.0018 ^T	0.295	0.001 ^W	0.020 ^T	0.0310	4.5	0.1 ^W
	598	19.1	12.9	7.5 ^T	0.0011 ^T	0.255	0.001 ^W	0.023 ^T	0.0385	3.7	0.1 ^W
	598	21.5	11.0	14.0	0.0021 ^T	0.220	0.001 ^W	0.010 ^W	0.0320	3.4	0.2 ^T
02-Nov-10	235	12.5	12.9	23.0	0.0041	0.255	0.001 ^W	0.143	0.0225	4.2	0.2 ^W
	229	16.5	12.3	14.5	0.0030	0.245	0.001 ^W	0.043 ^T	0.0165	4.2	0.2 ^T
	596	18.4	14.9	12.0	0.0029	0.230	0.001 ^W	0.041 ^T	0.0145	4.1	0.2 ^T
	595	22.8	11.2	9.5	0.0023 ^T	0.230	0.002 ^T	0.016 ^T	0.0200	4.0	0.2 ^T
	236	22.4	11.3	13.0	0.0021 ^T	0.225	0.001 ^W	0.010 ^W	0.0150	4.0	0.2 ^T
	237	19.7	12.0	12.5	0.0021 ^T	0.225	0.001 ^W	0.010 ^W	0.0140	3.5	0.2 ^T
238	15.0	11.1	11.0	0.0021 ^T	0.220	0.001 ^W	0.015 ^T	0.0145	3.4	0.2 ^T	

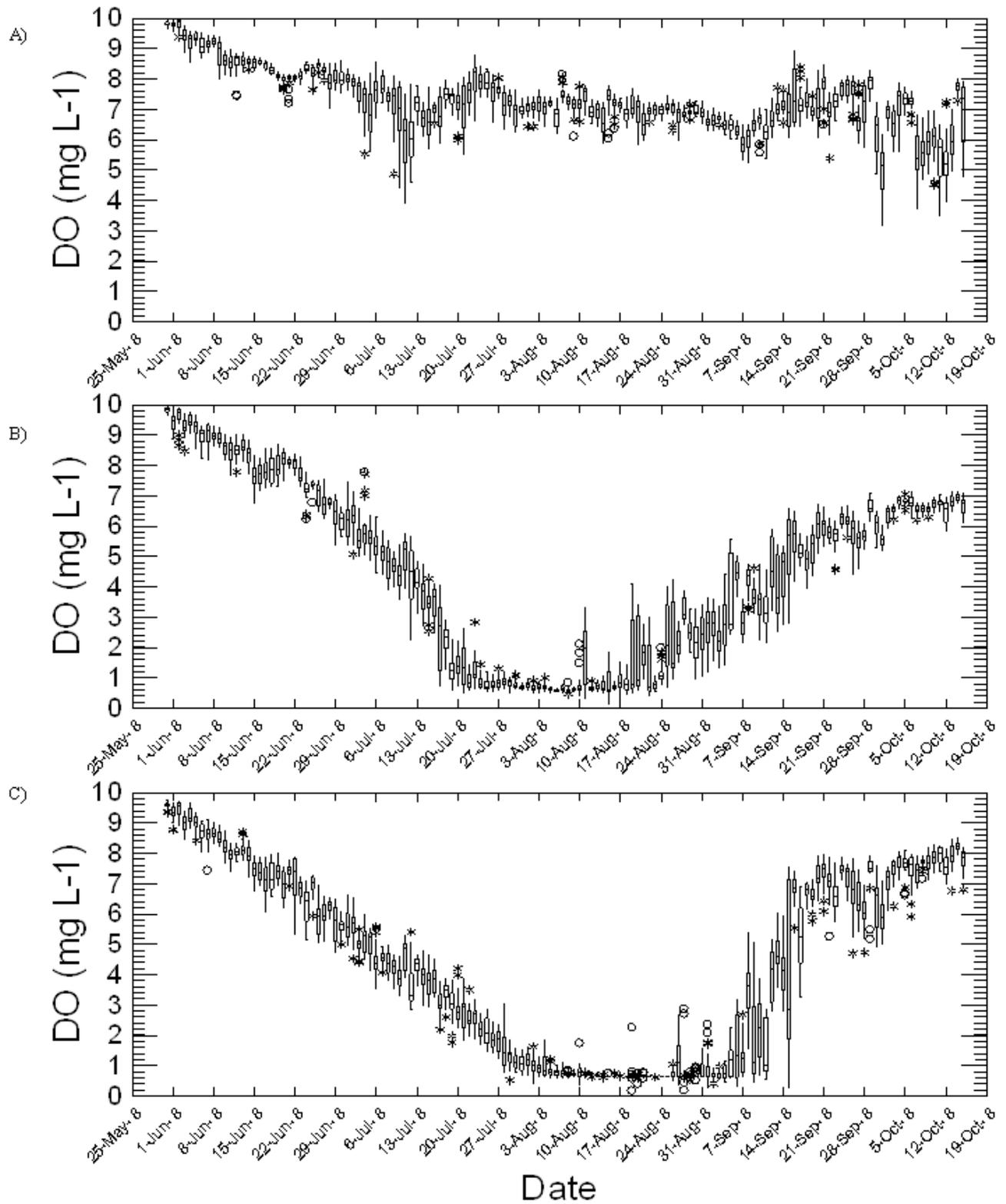
T A measurable trace amount
W Below the method detection limit

APPENDIX 2 Summary of epilimnetic nutrient and chlorophyll a concentrations in 2011, Lake Wolsey

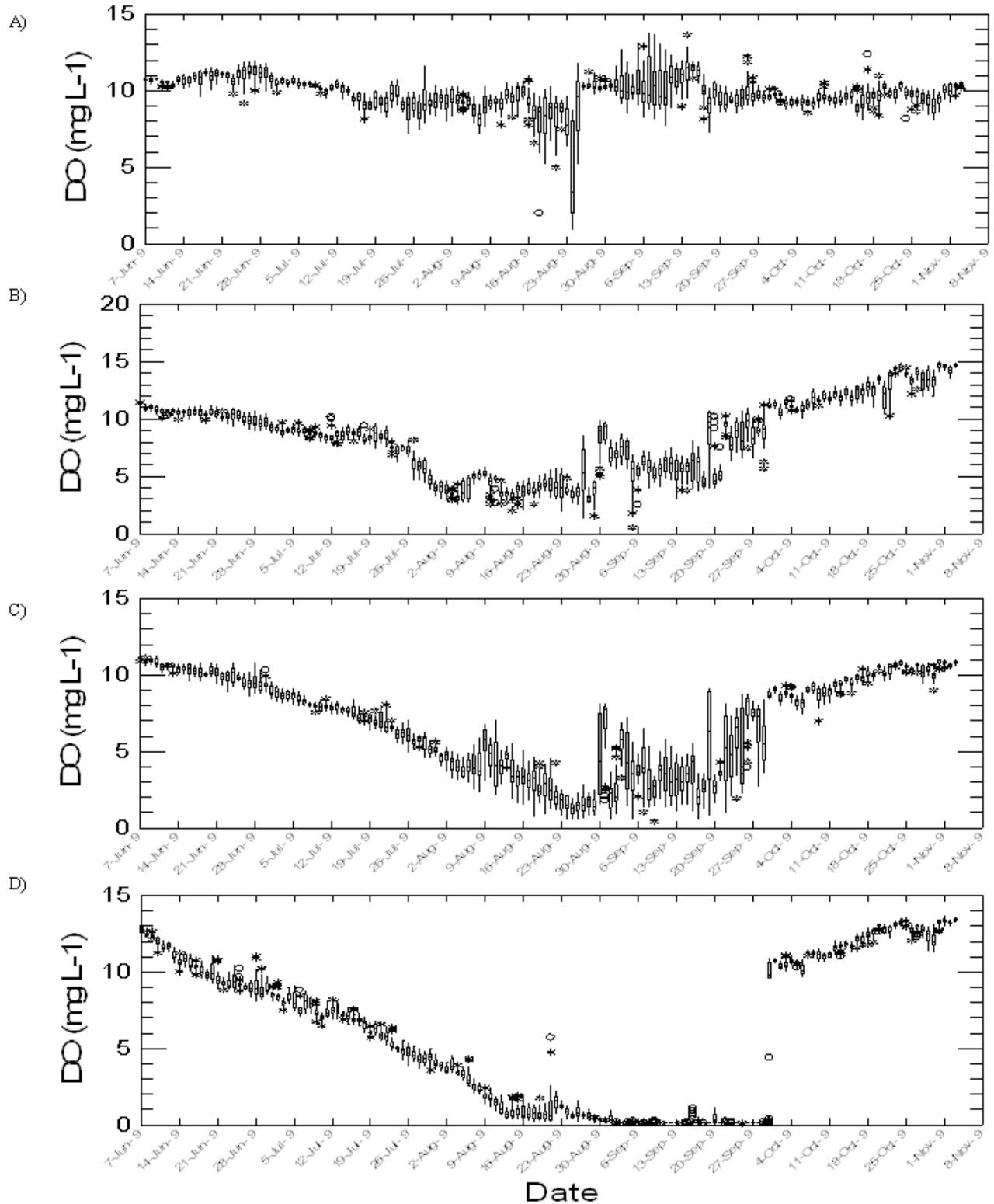
Survey	Station	Water Depth (m)	Total Phosphorus	Total Phosphorus	Phosphate (mg L ⁻¹)	Total Kjeldahl Nitrogen	Nitrite (mg L ⁻¹)	Nitrate (mg L ⁻¹)	Total Ammonium	Chlorophyll a (µg L ⁻¹)
			(Dorset; µg L ⁻¹)	(LaSB; µg L ⁻¹)		(mg L ⁻¹)			(mg L ⁻¹)	
6-May-11	229	16.8	9.4	2.5 ^T	0.0020	0.235	0.001	0.010 ^w	0.0400	3.5
	595	22.9	9.6	7.0 ^T	0.0020	0.240	0.002	0.010 ^w	0.0400	3.5
	596	19.5	9.0	7.5 ^T	0.0020	0.245	0.001	0.010 ^w	0.0410	3.5
	598	20.7	10.8	9.5	0.0030	0.250	0.001	0.010 ^w	0.0370	3.5
9-Aug-11	229	16.8	12.5	8.5 ^T	0.0010	0.265	0.001	0.024 ^T	0.0220	3.6
	595	23.5	11.9	7.7 ^T	0.0030	0.247	0.001	0.039 ^T	0.0310	3.1
	596	18.2	13.0	10.0	0.0020	0.260	0.001	0.037 ^T	0.0250	3.3
	598	22.4	11.8	7.0 ^T	0.0020	0.250	0.001	0.032 ^T	0.0340	2.9
24-Oct-11	229	16.7	17.0	21.0	0.0050	0.270	0.002	0.306	0.0260	3.1
	595	22.8	18.4	20.0	0.0050	0.260	0.002	0.010 ^w	0.0240	3.2
	596	18.9	17.1	19.5	0.0050	0.255	0.002	0.349	0.0240	3.1
	598	21.7	16.3	21.5	0.0060	0.280	0.002	0.010 ^T	0.0290	2.6

^T A measurable trace amount

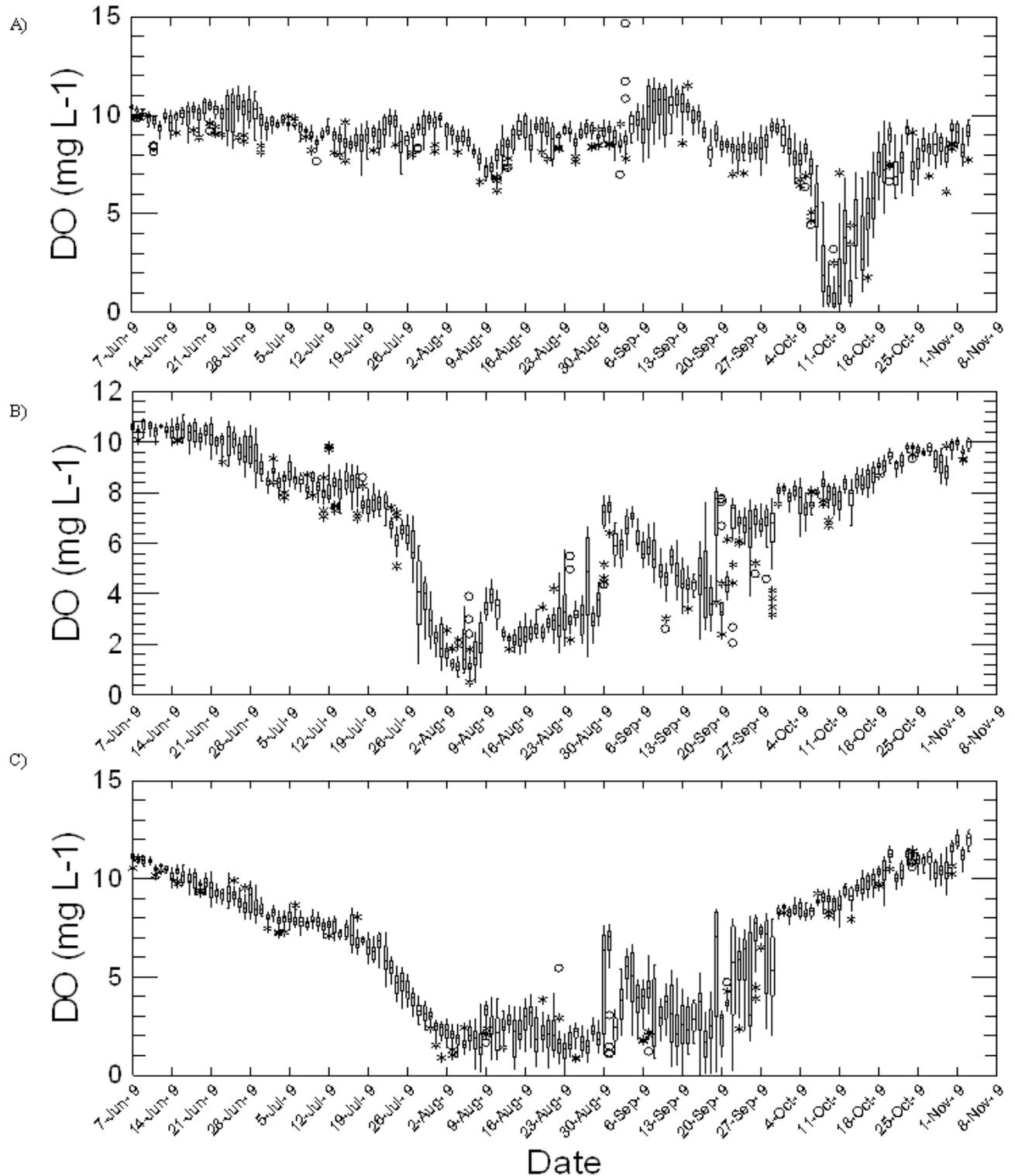
^w Below the method detection limit



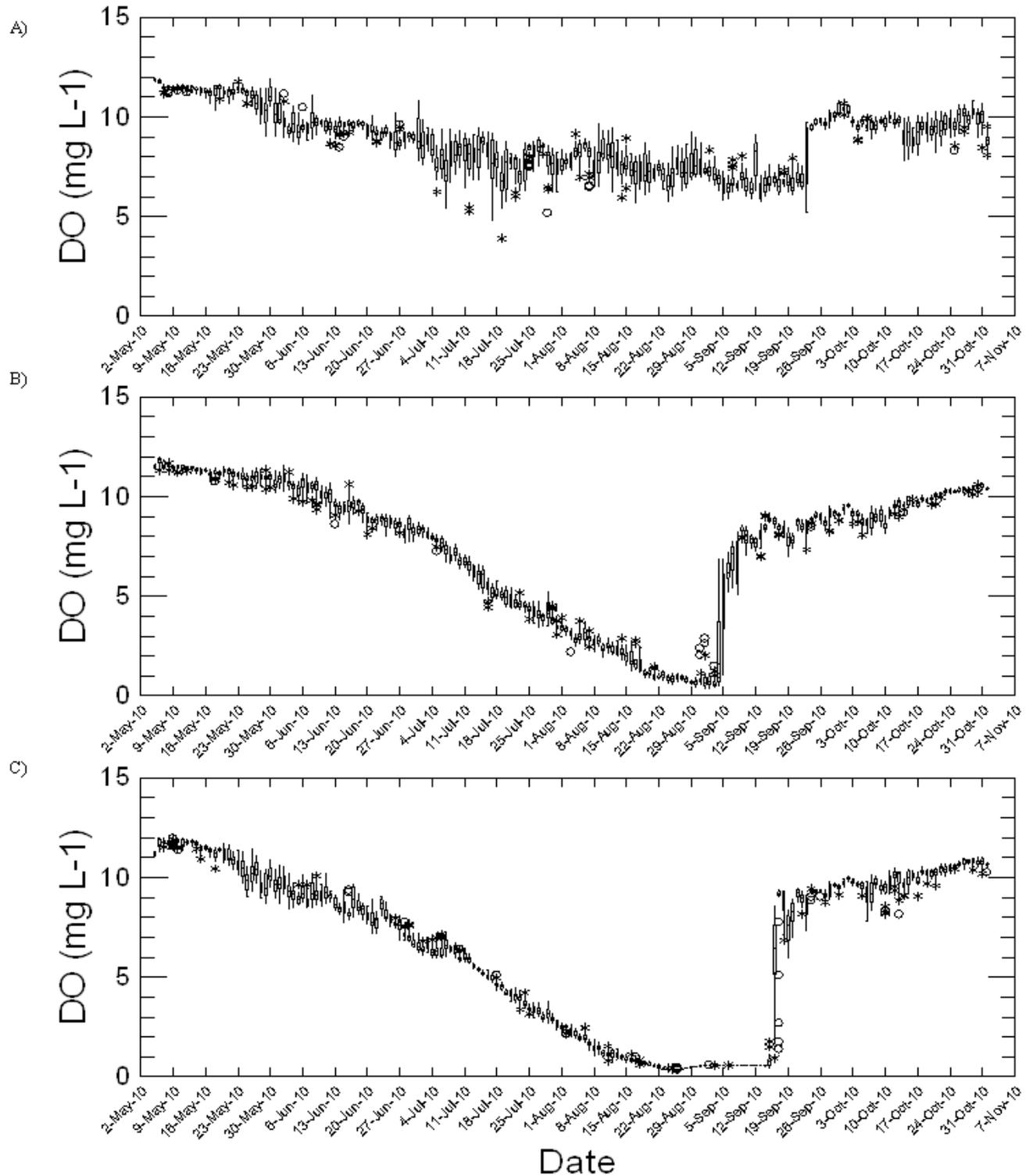
APPENDIX 3 Dissolved oxygen (mg L⁻¹) trends at Station 596 at a) 5 m b) 15 m and c) 17 m during the 2008 ice-free season, Lake Wolsey



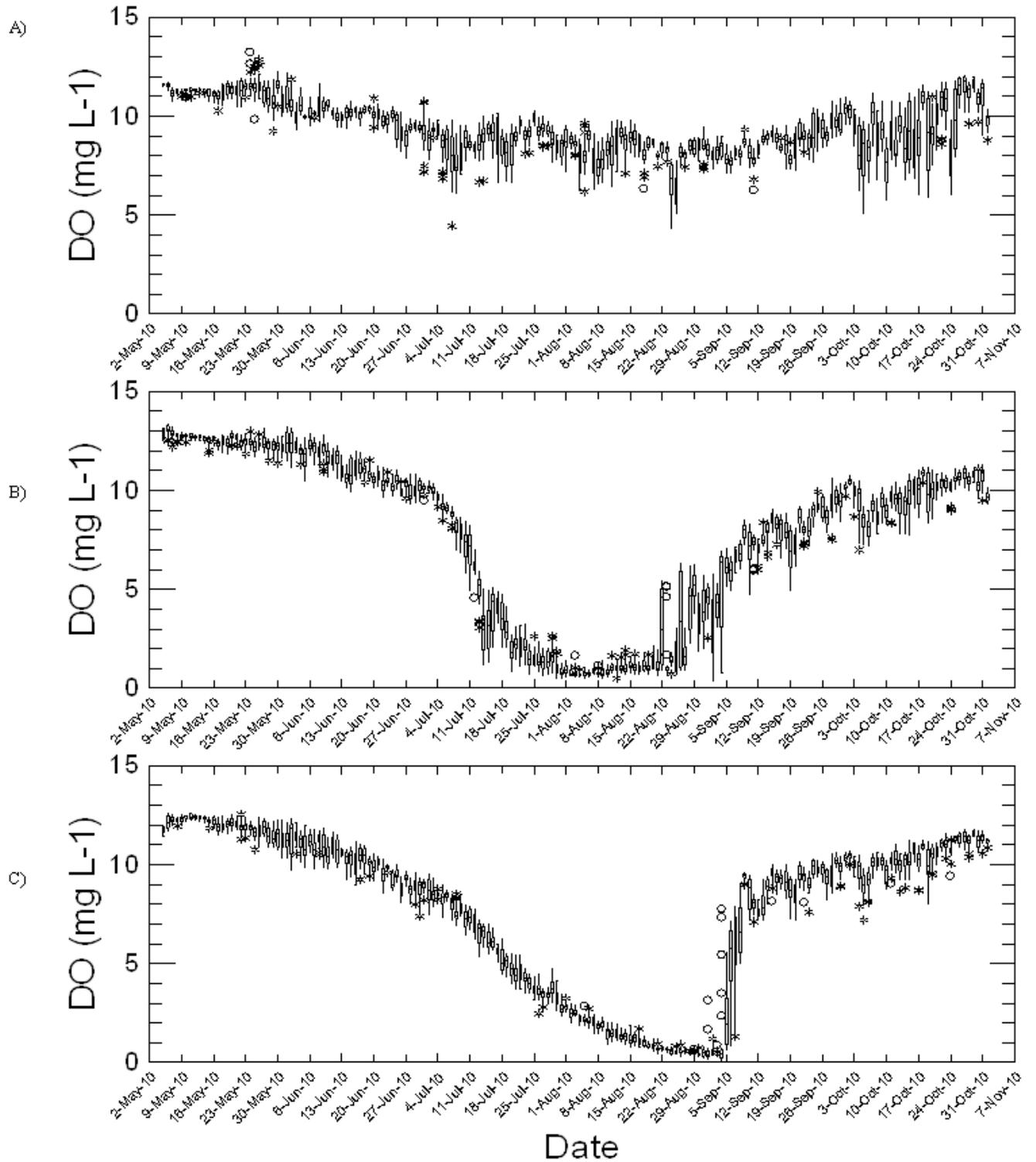
APPENDIX 4 Dissolved oxygen (mg L⁻¹) trends at Station 595 at a) 5 m b) 15 m c) 17 m and d) 22 m during the 2009 ice-free season, Lake Wolsey



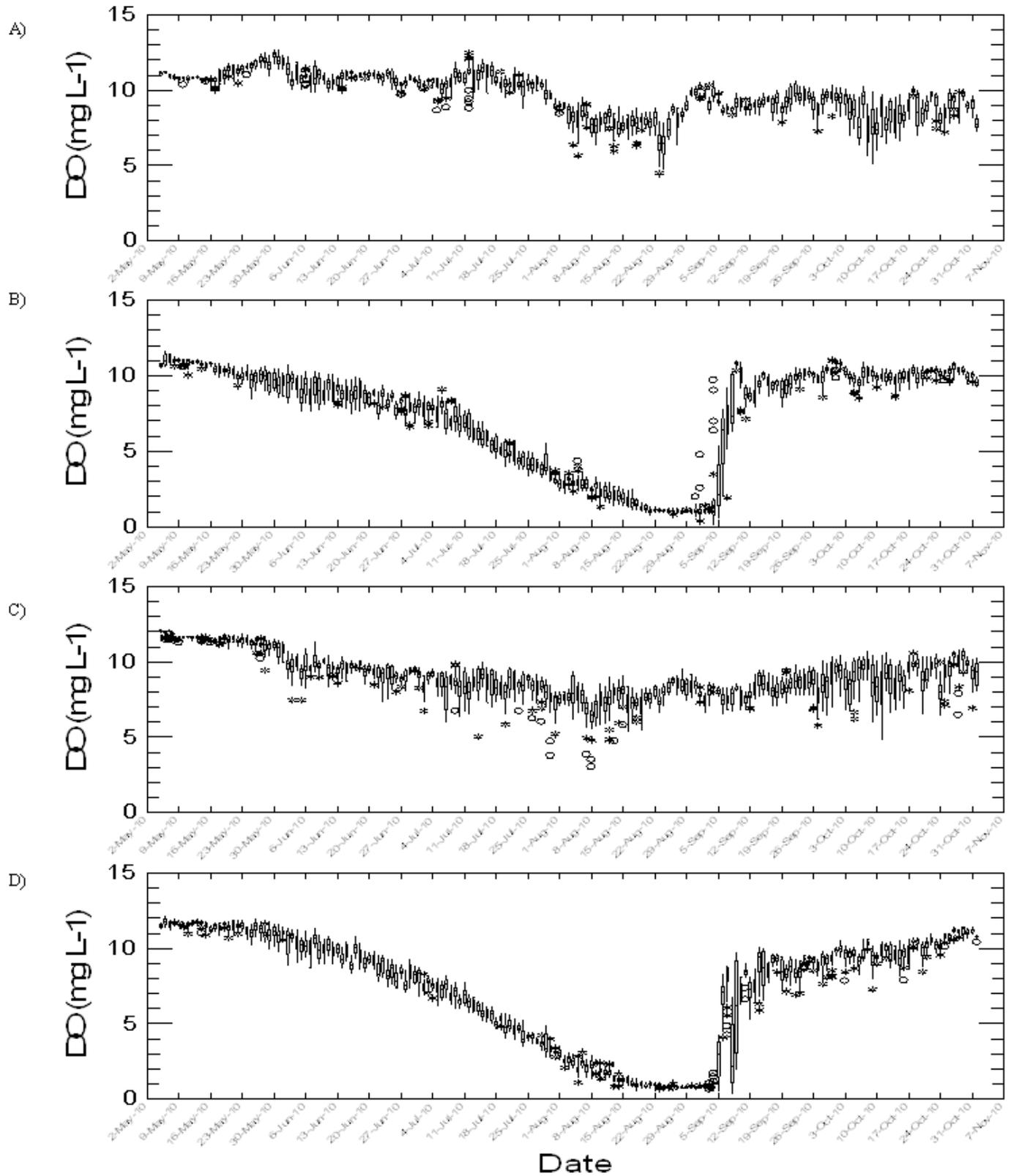
APPENDIX 5 Dissolved oxygen (mg L⁻¹) trends at Station 596 at a) 5 m b) 15 m and c) 17 m during the 2009 ice-free season, Lake Wolsey



APPENDIX 6 Dissolved oxygen (mg L⁻¹) trends at Station 595 at a) 4.9 m b) 16.9 m and c) 21.9 m during the 2010 ice-free season, Lake Wolsey



APPENDIX 7 Dissolved oxygen (mg L^{-1}) trends at Station 596 at a) 5.7 m b) 15.7 m and c) 17.7 m during the 2010 ice-free season, Lake Wolsey



APPENDIX 8 Dissolved oxygen (mg L⁻¹) concentrations at Station 229 at a) 5.8 m and b) 17.8 m and at Station 598 at c) 6.0 m and d) 18.0 m during the 2010 ice-free season, Lake Wolsey