Long-Term Dissolved Oxygen and Temperature Monitoring in Hamilton Harbour, Lake Ontario (2006-2013)

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By

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ABSTRACT

Dissolved oxygen is an important component of fish habitat. It affects where fishes can live, and their survival, growth rates and behaviour. Adequate knowledge of dissolved oxygen conditions is an important consideration when evaluating the habitat area available or its suitability to the fish community. In this report, we present long-term dissolved oxygen monitoring data for Hamilton Harbour, an embayment in western Lake Ontario. Dissolved oxygen was monitored on a semi-continuous basis at four stations in the harbour from 2006 to 2013. Dissolved oxygen depletion occurs regularly in the hypolimnion during the summer months, and the time period and variability of this depletion differ across the harbour. The dissolved oxygen data in this report will be incorporated into fish habitat assessments for the Hamilton Harbour Remedial Action Plan.

RÉSUMÉ

L'oxygène dissous est un constituant essentiel de l'habitat du poisson. Il a une incidence sur le lieu de vie des poissons et sur leur survie, leur taux de croissance et leur comportement. Les concentrations en oxygène dissous constituent un facteur important à prendre en considération pour évaluer la zone d'habitat disponible ou déterminer si elle convient à une communauté de poissons. Dans ce rapport, nous présentons les données de surveillance à long terme de l'oxygène dissous et température pour le port de Hamilton, une échancrure dans la partie ouest du lac Ontario. Le niveau d'oxygène dissous a été surveillé sur une base semi-continue dans quatre stations du port de 2006 à 2013. L'appauvrissement en oxygène dissous se produit régulièrement dans l'hypolimnion pendant les mois d'été et la période comme la variabilité de ce phénomène diffèrent dans les différents points du port. Les mesures de l'oxygène dissous indiquées dans le présent rapport seront intégrées aux évaluations de l'habitat du poisson réalisées dans le cadre du Plan d'assainissement du port de Hamilton.

INTRODUCTION

Dissolved oxygen (DO) is a vital factor affecting fishes in all aquatic ecosystems. Fishes require adequate levels of DO to survive and carry out life history processes. Widespread DO depletion, or hypoxia, has been observed in both marine and freshwater systems throughout the world, especially in regions affected by cultural eutrophication (Diaz 2001). The results of hypoxia range from mass fish kills to physiological stress, habitat loss, changes in fish communities and altered life history processes (Davis 1975; Chapman 1986). Given the range of potential effects low DO can have on fishes, DO is a crucial variable to include in fish habitat and population assessments if DO is impaired.

In 1987 under the Great Lakes Water Quality Agreement, 43 areas in the Laurentian Great Lakes were designated as Areas of Concern (AOCs). Areas listed were considered degraded environments as a result of contamination and water quality degradation due to anthropogenic activities. Concerns over DO depletion stem mainly from processes related to cultural eutrophication in the harbour; however, contaminants can also affect chemical oxygen demand (COD) and interact with biological oxygen demand (BOD) to affect aquatic life (Diaz 2001; Pollock et al. 2007).

Hamilton Harbour is a 2,150 hectare embayment located at the western end of Lake Ontario (Figure 1). The harbour is connected to Lake Ontario through a narrow channel called the Burlington Canal. Hamilton Harbour and its watersheds were designated as an AOC because of severe degradation owing to intense urban and industrial development (RAP 1992). The harbour was subject to contamination from iron and steel industries, eutrophication from urban development, and four wastewater treatment plants that discharged effluents into the relatively enclosed harbour.

The Hamilton Harbour Remedial Action Plan (RAP) includes DO targets under the Beneficial Use Impairment (BUI) ‘Eutrophication.’ Currently targets are >6 mg/l over a 4-m depth range but >3 mg/l over a 2 m depth range during allowable exceedance periods (2 out of 17 weekly sample dates from June to September) in the harbour, and >5 mg/l in Cootes Paradise (Bowlby et al. 2010). These targets are related to the required

DO concentrations for Cisco (*Coregonus artedi*; Lake Herring), a sensitive and desired fish species that occupies the cold midwater layer of water above or below the thermocline (Bowlby et al. 2010). Historically, Cisco dominated the commercial fishing catch in western Lake Ontario (Bowlby et al. 2010). A DO target for Cisco would provide adequate DO habitat for the whole fish community in Hamilton Harbour.

Although historical DO data for Hamilton Harbour are lacking, it is believed that longterm and widespread DO depletion in the harbour is related to cultural eutrophication where high phosphorus concentrations result in high primary production. As primary producers die and sink to the bottom of the lake, oxygen is utilized for their decomposition. As a result, during summer stratification when the hypolimnion is isolated from oxygenated surface waters, it can experience hypoxic or even anoxic conditions. Eutrophic dimictic or monomictc lake systems often experience hypoxia or even anoxia in the hypolimnion during late summer months before turnover in the fall. Hamilton Harbour was historically an oligotrophic to mesotrophic system with a rich fish community (Yang et al. 1993; Holmes and Whillans 1984; Bowlby et al. 2010). This suggests that the harbour did not historically experience summer hypolimnetic oxygen depletion, although given its deeper and cone-shaped morphology it may have experienced low dissolved oxygen periods during late summer months.

Given that Hamilton Harbour currently experiences hypoxia during summer months and low DO can have adverse effects on fishes, it is important to take DO conditions into consideration when evaluating the fish habitat BUI for the RAP. Although DO data have been collected for various purposes (e.g., Charlton 2001) and DO profiles have been taken weekly or bi-weekly at the centre of the harbour during the ice-free season since 1987 (Hiriart-Baer et al. 2009), these data may not provide a representative picture of the spatial dynamics of DO in the entire harbour. To adequately inform specific habitat restoration actions, a comprehensive fish habitat assessment requires a good understanding of how DO changes over time and space within the harbour at a finer scale than the whole basin. Since 2006, we have undertaken a long-term, relatively continuous DO monitoring program at several stations in Hamilton Harbour. The deployments

focused on spatial differences, including nearshore differences around the harbour, during the summer hypoxic period and also overwinter, which had not been evaluated previously. The results from the monitoring program will be incorporated into water quality and fish habitat assessments for the Hamilton Harbour RAP.

METHODS

Since 2006, Fisheries and Oceans Canada (DFO)'s Great Lakes Laboratory for Fisheries and Aquatic Sciences (GLLFAS), in conjunction with scientists from Environment Canada and the Ontario Ministry of Natural Resources and Forestry, have deployed long-term dissolved oxygen loggers in Hamilton Harbour on a regular basis. Loggers have been deployed in both the ice-free and winter seasons. In each season, loggers were deployed at up to four stations throughout the harbour: Centre, West, LaSalle and STP stations (Figure 1). Centre station is located at the deepest point of the harbour and is approximately 23-m deep. The three other stations each have a maximum depth of approximately 8 m.

Long-term DO monitoring in the harbour used four types of instruments: Hydrolab DataSonde 5, Yellow Springs Instrument (YSI) 6-Series Sonde, HOBO U26 Dissolved Oxygen Loggers, and a YSI profiling buoy (herein after called 'Profiler'). The Hydrolab, YSI and HOBO loggers are moored in place at a given depth, whereas the Profiler travels from the bottom to surface to record data through the water column at set intervals. While all instruments record similar parameters (e.g., temperature and DO), in later years the YSIs, HOBO loggers and Profilers were preferred because of their ability to maintain a longer battery life. For accurate DO readings, Hydrolabs must have a battery charge greater than 7 volts (HACH 2006), YSIs must have a DO charge that is greater than 25% charge and remains relatively stable (Yerubandi, pers. comm.), and the sensor cap on the HOBO loggers should be replaced every six months for optimal performance (Onset 2013). The battery charge in Hydrolabs relates to the accuracy of data collection from the luminescent DO sensor. The DO-charge parameter in YSIs is a

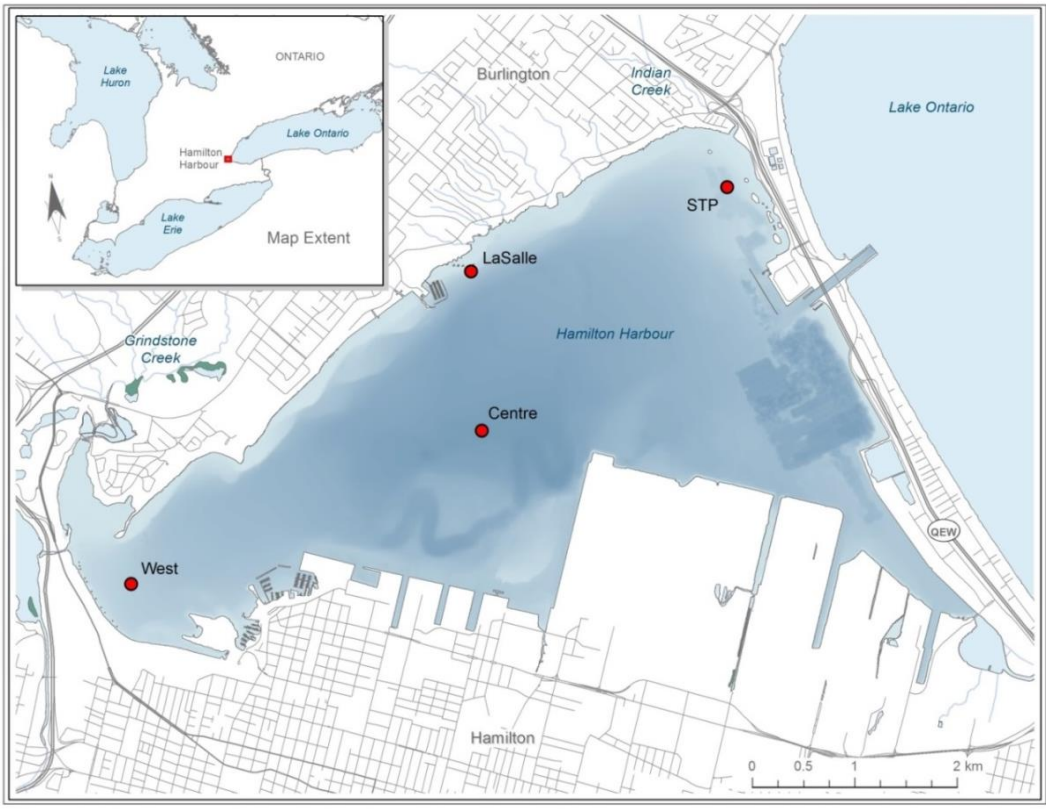

Figure 1. Map of Hamilton Harbour showing the four long-term dissolved oxygen monitoring stations. The inset map shows the location of Hamilton Harbour in the Laurentian Great Lakes.

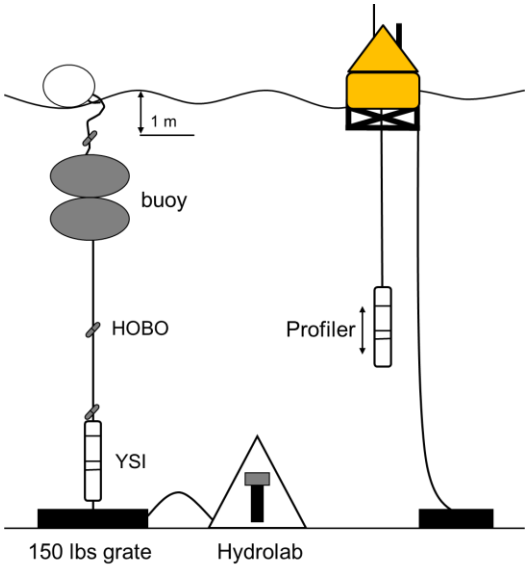

Figure 2. Design of water quality mooring stations. The dissolved oxygen monitoring instrument (Hydrolab or YSI) is mounted on a triangular or U-shaped frame 1 m off the bottom. The frame is connected to a line with a surface (ice-free season) or sub-surface (ice season) buoy. In later periods, YSIs are suspended in line with the buoys and additional instruments including HOBO loggers are attached to the line for some stations (Table 1). The Profiler travels up and down the water column at Center station (Figure 1).

sensor diagnostic value and relates to electrolytes in the membrane. We used this information to filter our data for uncertainty and its reliability.

Prior to each deployment, the instruments were calibrated. Calibration ensures more accurate parameter readings. Hydrolab, YSI and HOBO instruments were programmed to record DO, temperature, and battery or 'DO charge' hourly from the date of deployment until retrieval. Moored loggers were deployed at 1-m above the station bottom depth on a triangular or u-shaped frame leading to a surface (during ice-free season) or sub-surface buoy (during winter; Figure 2). Some exceptions to this deployment depth occurred at the Centre station and are noted in Table 1.

The Profiler was programmed to record DO, temperature, specific conductance, pH and depth. The instrument was programmed to conduct a depth profile every 120 minutes; however, the exact interval varied. During each time interval, the profiler began at the deepest point (~23 m depth) and recorded the parameters at approximately one metre intervals from the bottom to surface.

Upon retrieval, data were examined for quality assurance. Data points at the beginning of the data series were removed until the point in the series where it was clear the logger had deployed and stabilized in the water column. Data points at the end of the series occurring after retrieval were likewise removed. The data series were examined for further issues due to failures of parameter sensors and batteries. Quality-assured data were summarized into figures showing trends over time and average dissolved oxygen by month, and into histograms showing the frequency of the development of low DO conditions (<6 mg/l and <3 mg/l). These two DO levels are used to determine the amount of vertical habitat available to sensitive fish species such as Cisco in the water column (Bowlby et al. 2014). Exceedance of these thresholds across years by spatial location was calculated.

Table 1. Summary of long-term dissolved oxygen monitoring deployments in Hamilton Harbour. Site, instrument depth, deployment and retrieval dates, start and end dates to which the final data series were clipped, and any issues with the data are noted. Dissolved oxygen loggers were identified as Y=YSI, H=Hydrolab and D=HOBO logger. The figure number in this document where the data are presented is included if applicable.

Site	Depth (m)	Deployment Date	Retrieval Date	Sample Start Date	Sample End Date	Logger	Figure	Notes
Centre	13	Nov-26-2007	Apr-07-2008	Nov-26-2007	Mar-11-2008	Y	4	Unstable DO charge indicates possible failure
Centre	13	Dec-10-2008	Apr-09-2009	Dec-10-2008	Apr-09-2009	Y	5	
Centre	13	Dec-02-2009	Apr-08-2010	Dec-02-2009	Apr-08-2010	Y	6	
Centre	22	Nov-26-2007	Apr-07-2008	Nov-26-2007	Apr-07-2008	Y	7	
Centre	22	Dec-10-2008	Apr-09-2009	Dec-10-2008	Apr-07-2009	Y	8	
Centre	22	Dec-02-2009	Apr-08-2010	Dec-02-2009	Apr-08-2010	Y	9	
Centre	22	Dec-10-2010	Apr-13-2011	-	-	Y	-	Instrument failure
Centre	0-23	May-10-2011	Nov-10-2011	May-10-2011	Nov-10-2011	P	23	
Centre	0-23	May-11-2012	Oct-24-2012	May-11-2012	Oct-24-2012	P	24	Data quality could not be verified
LaSalle	7	May-10-2006	Jul-19-2006	May-10-2006	Jul-19-2006	H	10	
LaSalle	7	Jul-21-2006	Sep-22-2006	Jul-21-2006	Sep-22-2006	H	10	
LaSalle	7	Sep-28-2006	Nov-27-2006	Sep-28-2006	Nov-27-2006	H	10	
LaSalle	7	Jan-08-2008	Apr-07-2008	-	-	Y	-	High DO values indicate instrument failure
LaSalle	7	Dec-02-2009	Apr-08-2010	-	-	Y	-	Instrument failure
LaSalle	7	Apr 25, 2013	Aug 1, 2013	Apr 25, 2013	Aug 1, 2013	D	11	
STP	7	May-11-2006	Jul-19-2006	May-11-2006	Jul-08-2006	H	12	↓ battery below 7V after July 8
STP	7	Jul-21-2006	Sep-22-2006	Jul-21-2006	Sep-20-2006	H	12	↓ battery below 7V after Sep 20
STP	7	Sep-28-2006	Nov-27-2006	Sep-28-2006	Nov-27-2006	H	12	
STP	7	May-25-2007	Jul-28-2007	-	-	H	-	Instrument failure
STP	7	Nov-21-2007	Apr-03-2008	Nov-22-2007	Dec-15-2007	Y	13	↓ DO charge after Dec 15 indicates failure
STP	9	Nov-21-2007	Apr-02-2008	Nov-21-2007	Mar-05-2008	Y	14	↓ DO charge indicates possible instrument failure
STP	7	Jul-29-2010	Dec-10-2010	Jul-29-2010	Nov-30-2010	H	15	↓ battery below 7V after Nov 30
STP	7	May-11-2011	Nov-27-2011	May-11-2011	Oct-27-2011	Y	16	Instrument failure near end of series
STP	7	May 5, 2012	Nov 21, 2012	May 5, 2012	Nov 21, 2012	Y	17	
STP	7	Apr 25, 2013	Aug 1, 2013	Apr 25, 2013	Aug 1, 2013	D	18	
West	7	May-10-2006	Jul-19-2006	May-10-2006	Jul-19-2006	H	19	
West	7	Jul-21-2006	Sep-22-2006	Jul-21-2006	Sep-22-2006	H	19	
West	7	Sep-28-2006	Nov-27-2006	Sep-28-2006	Nov-24-2006	H	19	↓ battery below 7V after Nov 24
West	7	May-25-2007	Jul-28-2007	May-25-2007	Jun-15-2007	H	20	↓ battery below 7V after June 15
West	7	May-07-2009	Jul-16-2009	May-07-2009	May-31-2009	H	21	Battery dies; possible instrument failure
West	7	Jul-30-2010	Dec-10-2010	-	-	H	-	Instrument failure
West	6	Dec-10-2010	Apr-07-2011	Dec-10-2010	Apr-07-2011	Y	22	
West	7	May-12-2011	Nov-27-2011	-	-	Y	-	Instrument failure
West	7	May 5, 2012	Nov 21, 2012	-	-	Y	-	Instrument failure

RESULTS

Long-term dissolved oxygen loggers were deployed at each station several times between 2006 and 2013 (Table 1; Figure 3). Through the data quality assurance process, we determined that for the moored deployments 74.71% of the samples were of good quality, 10.01% were of uncertain quality, and 15.28% were not recorded due to instrument failure (Figure 3). Useable data were collected during 84.3% of the time periods monitored at the mid-water column centre station, 69.54% at Centre Deep, 92.3% at STP, 75.01% at LaSalle and 90.6% at West station. Flagged, unusable data were largely due to instrument failure, DO charge loss or battery loss. These are noted for each deployment in Table 1.

The Profiler collected data at the Centre station from May 10 to November 10, 2011 and May 11 to October 24, 2012. Data were collected 96.6% of the time in 2011 and 50.1% of the time in 2012. While the data coverage is much better in 2011, both years show similar trends where the hypolimnion becomes hypoxic as soon as thermal stratification begins in the spring and continues through the fall until turnover occurs.

Data from each successful and unverified deployment (i.e. the QA/QC process could not verify data quality; 10.01% of data) are presented in a series of figures: Figures 4-6 show data from Centre-Mid station deployments, Figures 7-9 show Centre-Deep station deployments, Figures 10-11 show LaSalle station deployments, Figures 11-18 show STP station deployments, Figures 19-22 show West station deployments, and Figures 23-24 show the Centre station Profiler deployments.

In general, DO was higher on average during winter months than summer months across the harbour (Figure 25) but highly variable across the stations and across time. Dissolved oxygen concentrations in the winter infrequently decreased below 6 mg/l at all sites (Figures 26, 27, 30). At shallower sites, in the summer months (June to September), DO decreased below 6 mg/l for the majority of time at STP (Figure 29) and West (Figure 30) stations, and about half the time at LaSalle (Figure 28). Dissolved oxygen concentrations frequently fell below 3 mg/l at LaSalle, STP and West stations, with the

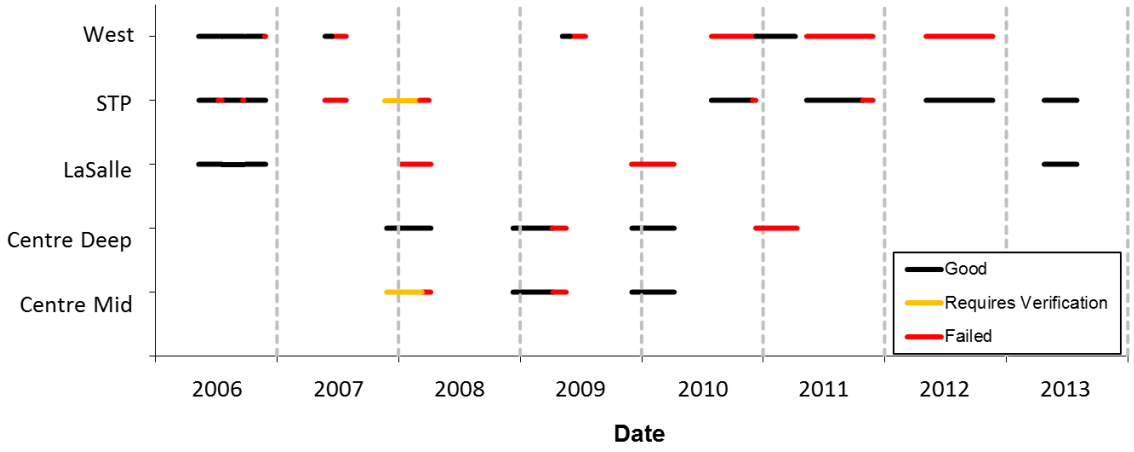

Figure 3. Summary of long-term moored dissolved oxygen deployments at Hamilton Harbour sites in 2006-2013. Time periods in black have good quality data, time periods in yellow require further evaluation, and time periods in red represent failed deployments. Additional details can be found in Table 1.

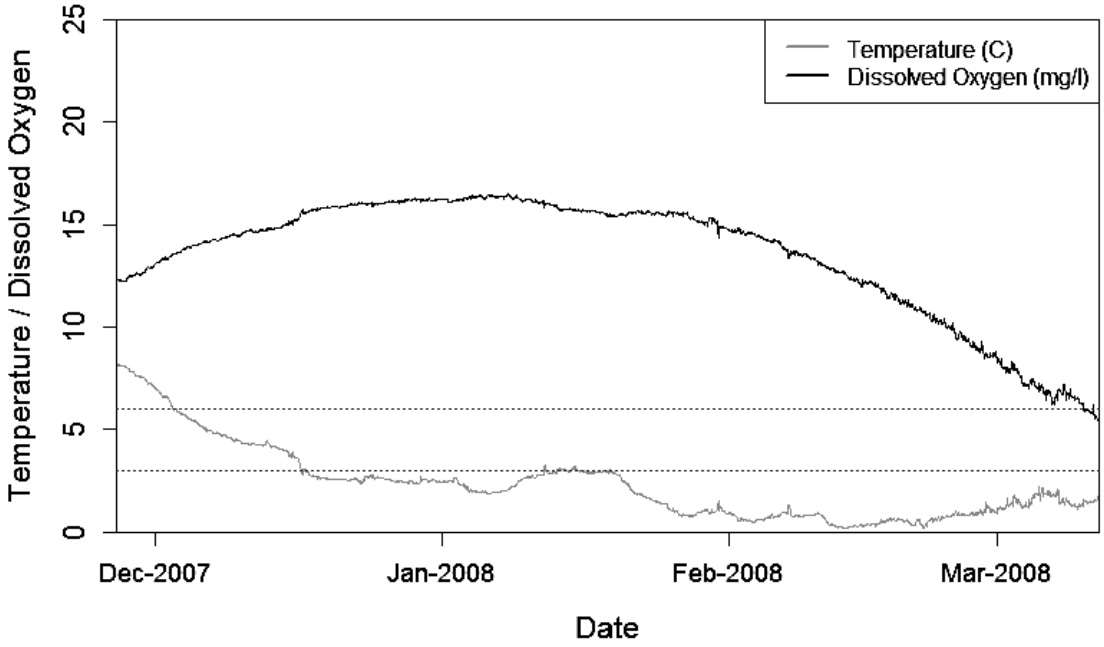

Figure 4. Long-term dissolved oxygen (mg/l) and temperature (ºC) deployment at Centre Mid from November 26, 2007 to March 11, 2008. Possible instrument failure during deployment. The dotted lines represent Hamilton Harbour Remedial Action Plan (RAP) delisting objectives for dissolved oxygen (Cisco layer; 6 mg/l and 3 mg/l).

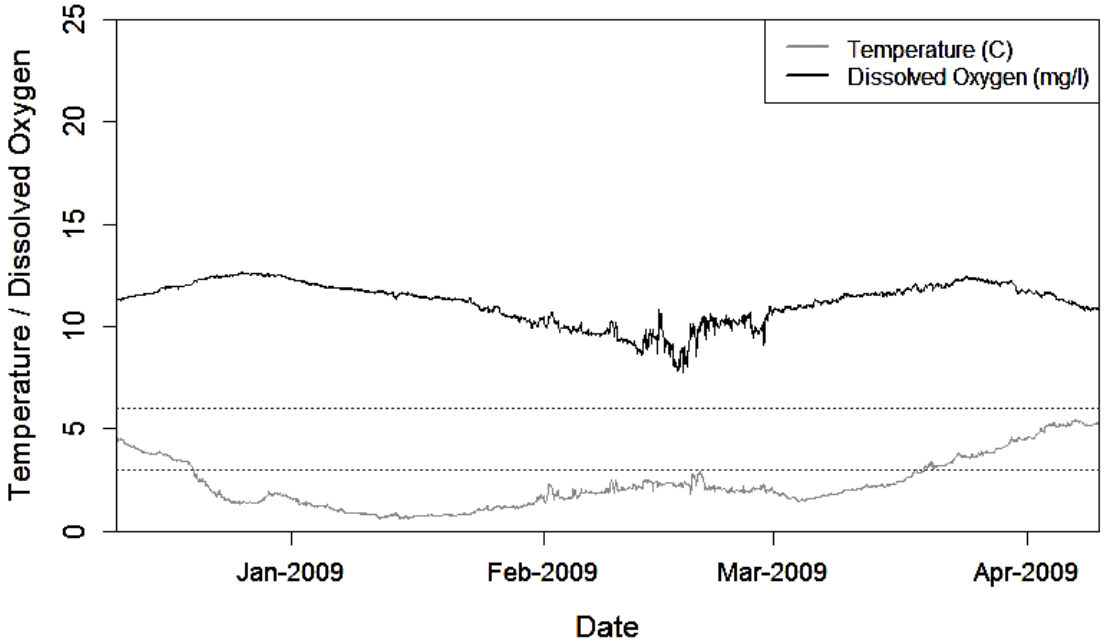

Figure 5. Long-term dissolved oxygen (mg/l) and temperature (ºC) deployment at Centre Mid from December 10, 2008 to April 9, 2009. The dotted lines represent Hamilton Harbour Remedial Action Plan (RAP) delisting objectives for dissolved oxygen (Cisco layer; 6 mg/l and 3 mg/l).

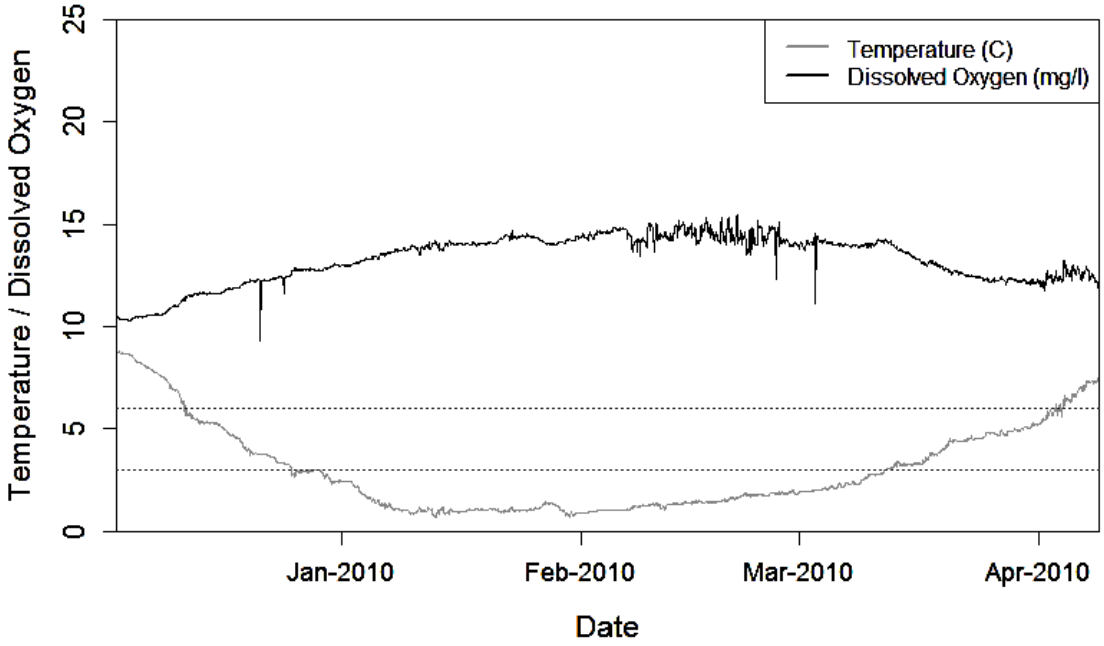

Figure 6. Long-term dissolved oxygen (mg/l) and temperature (ºC) deployment at Centre Mid from December 2, 2009 to April 8, 2010. The dotted lines represent Hamilton Harbour Remedial Action Plan (RAP) delisting objectives for dissolved oxygen (Cisco layer; 6 mg/l and 3 mg/l).

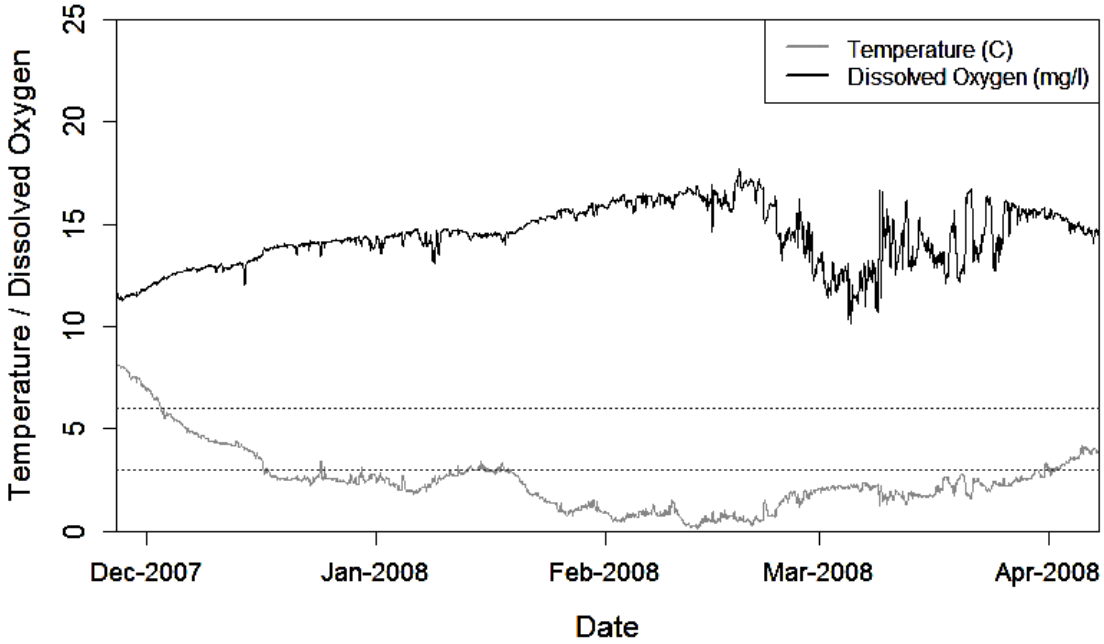

Figure 7. Long-term dissolved oxygen (mg/l) and temperature (ºC) deployment at Centre Deep from November 26, 2007 to April 7, 2008. The dotted lines represent Hamilton Harbour Remedial Action Plan (RAP) delisting objectives for dissolved oxygen (Cisco layer; 6 mg/l and 3 mg/l).

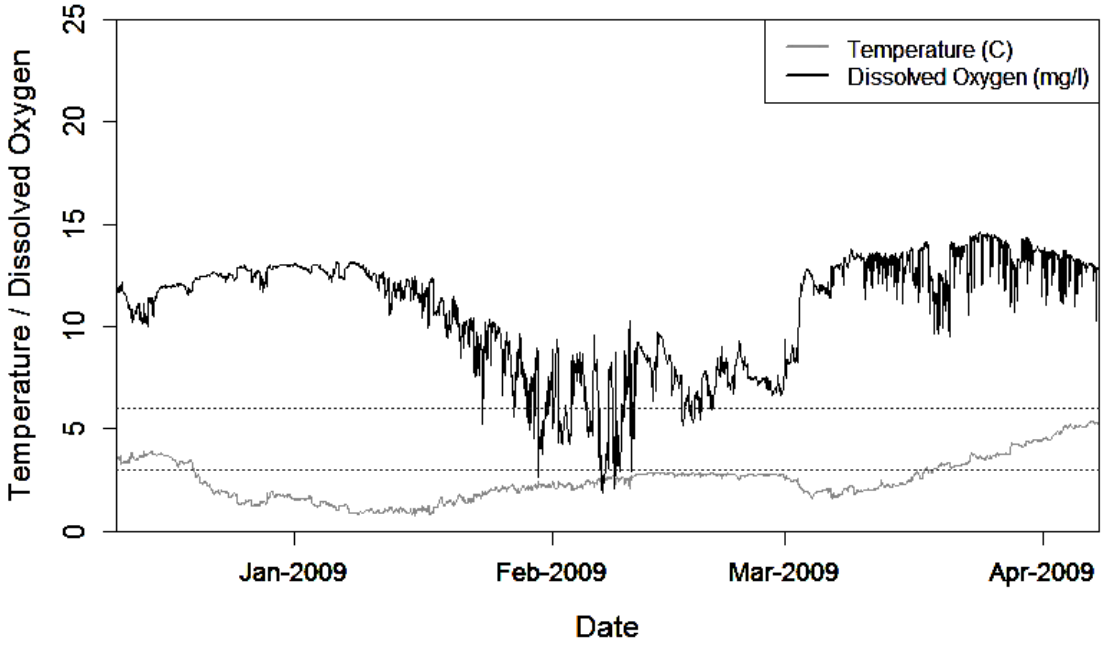

Figure 8. Long-term dissolved oxygen (mg /l) and temperature (ºC) deployment at Centre Deep from December 10, 2008 to April 7, 2009. The dotted lines represent Hamilton Harbour Remedial Action Plan (RAP) delisting objectives for dissolved oxygen (Cisco layer; 6 mg/l and 3 mg/l).

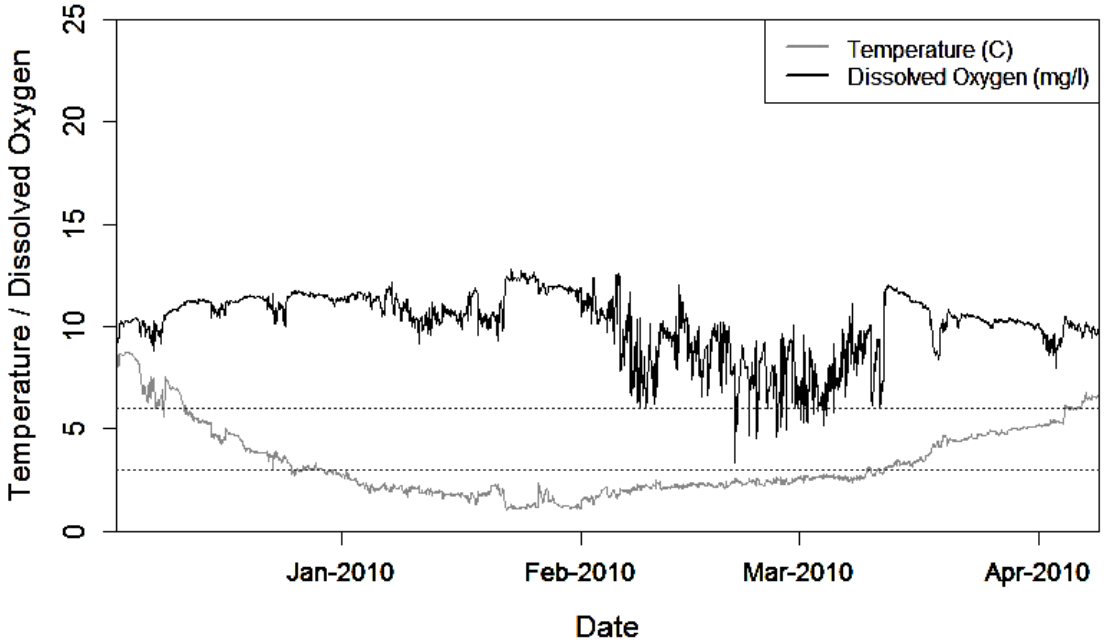

Figure 9. Long-term dissolved oxygen (mg/l) and temperature (ºC) deployment at Centre Deep from December 2, 2009 to April 8, 2010. The dotted lines represent Hamilton Harbour Remedial Action Plan (RAP) delisting objectives for dissolved oxygen (Cisco layer; 6 mg/l and 3 mg/l).

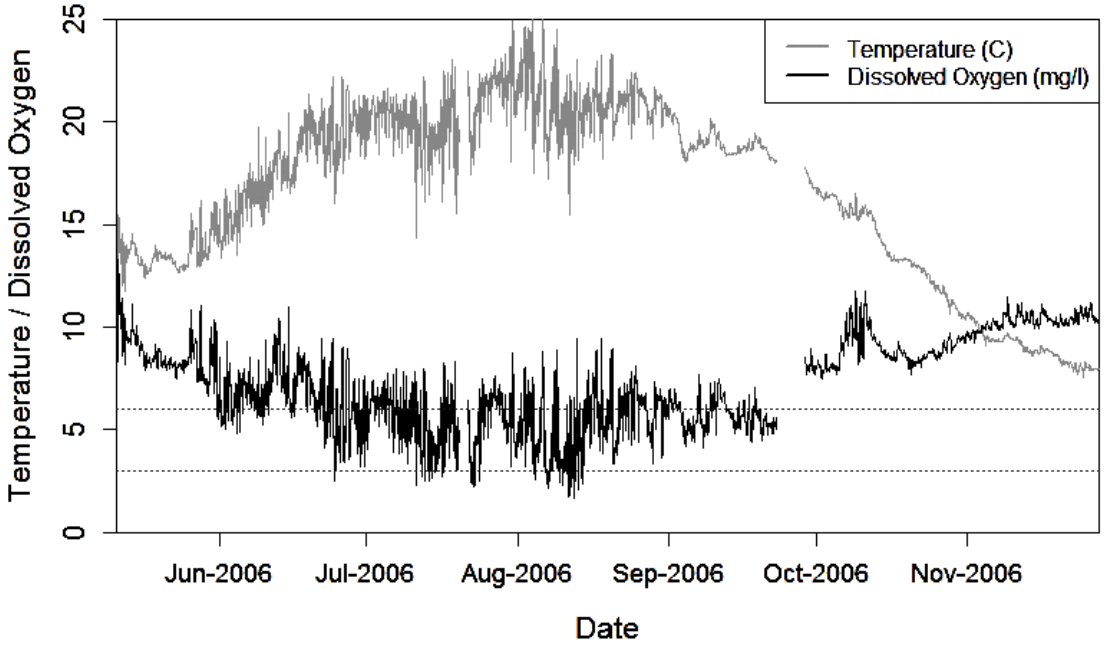

Figure 10. Long-term dissolved oxygen (mg/l) and temperature (ºC) deployment at LaSalle from May 10, 2006 to November 27, 2006. The dotted lines represent Hamilton Harbour Remedial Action Plan (RAP) delisting objectives for dissolved oxygen (Cisco layer; 6 mg/l and 3 mg/l).

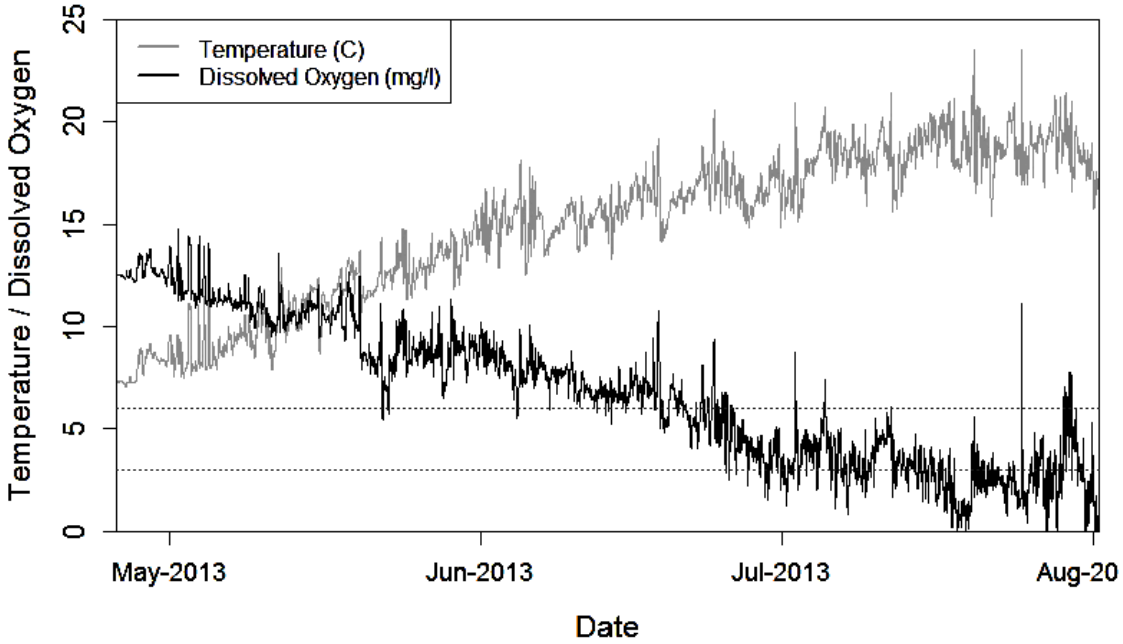

Figure 11. Long-term dissolved oxygen (mg/l) and temperature (ºC) deployment at LaSalle from April 25, 2013 to August 1, 2013. The dotted lines represent Hamilton Harbour Remedial Action Plan (RAP) delisting objectives for dissolved oxygen (Cisco layer; 6 mg/l and 3 mg/l).

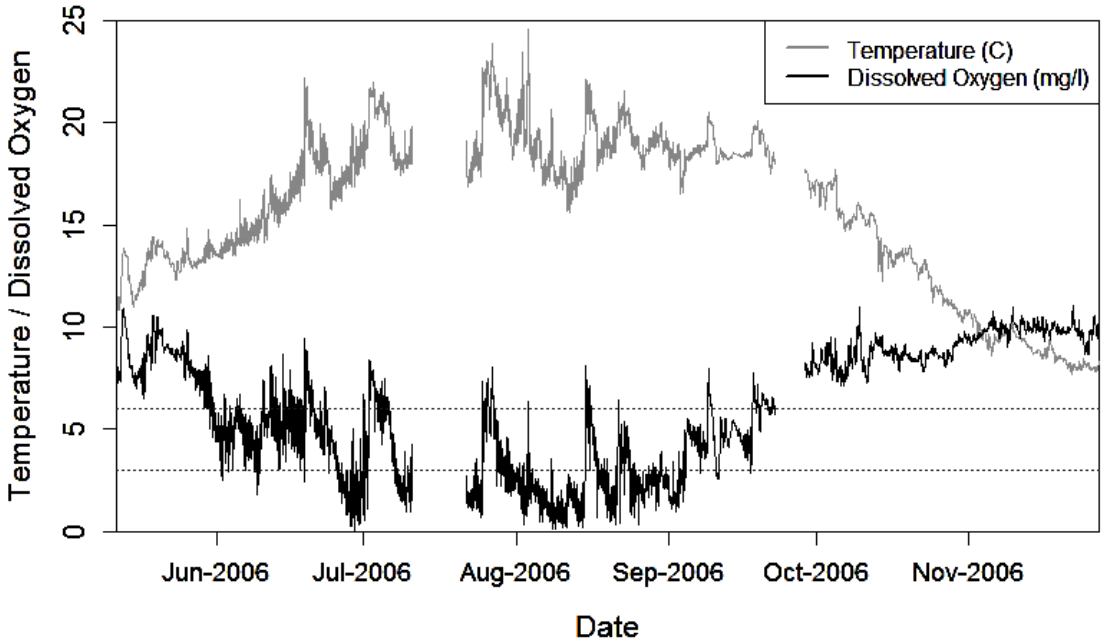

Figure 12. Long-term dissolved oxygen (mg/l) and temperature (ºC) deployment at STP from May 11, 2006 to November 27, 2006. The dotted lines represent Hamilton Harbour Remedial Action Plan (RAP) delisting objectives for dissolved oxygen (Cisco layer; 6 mg/l and 3 mg/l).

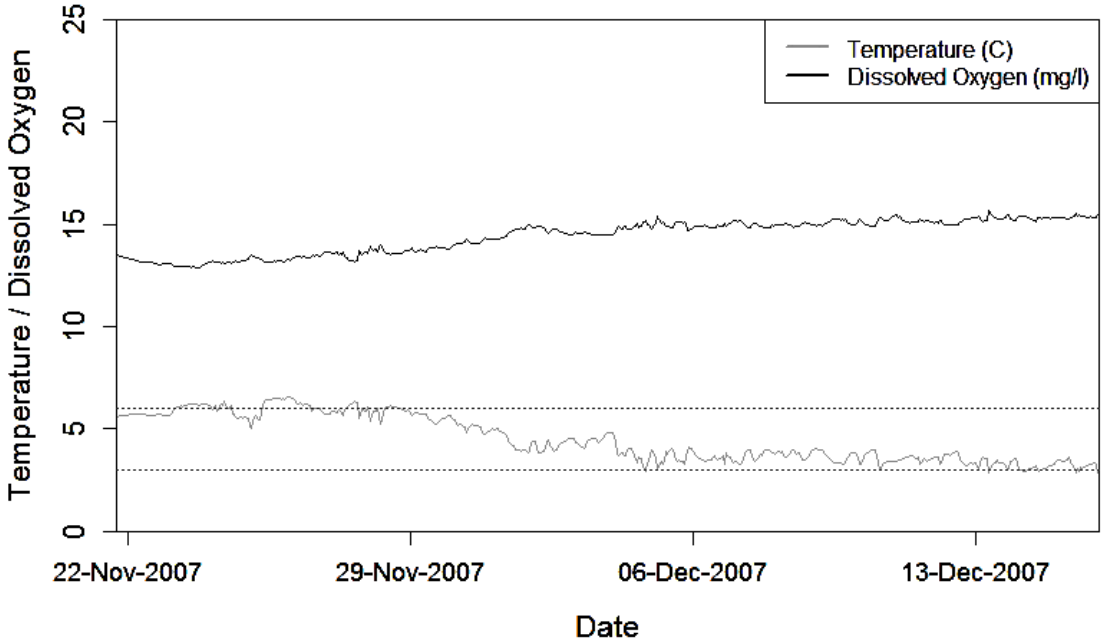

Figure 13. Long-term dissolved oxygen (mg/l) and temperature (ºC) deployment at STP from November 22, 2007 to December 15, 2007. The dotted lines represent Hamilton Harbour Remedial Action Plan (RAP) delisting objectives for dissolved oxygen (Cisco layer; 6 mg/l and 3 mg/l).

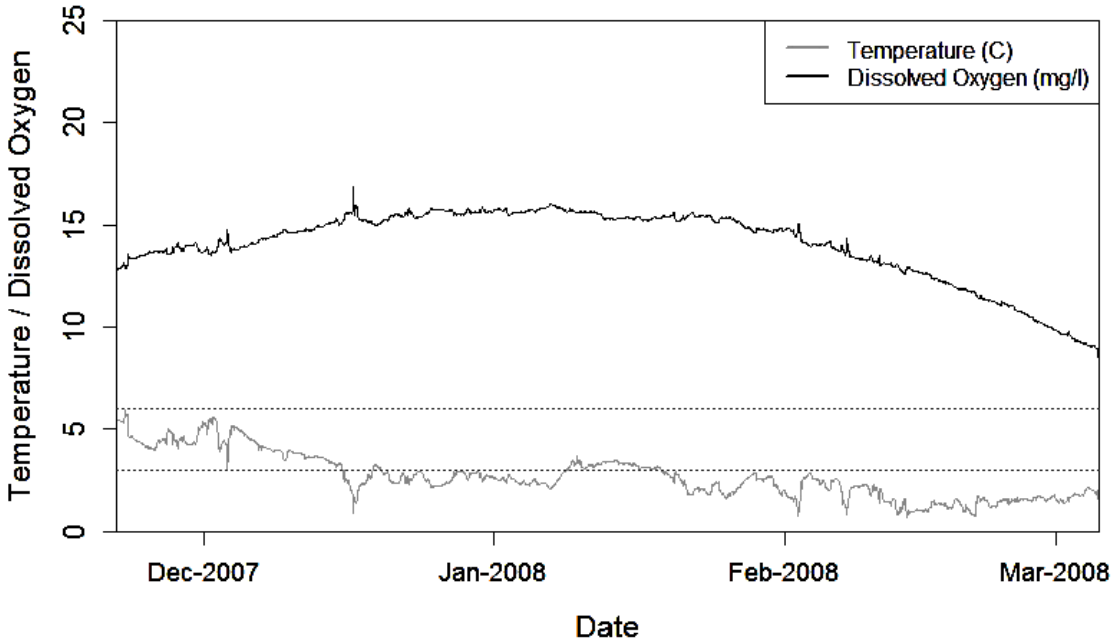

Figure 14. Long-term dissolved oxygen (mg/l) and temperature (ºC) deployment at STP from November 21, 2007 to March 5, 2008. Possible instrument failure during deployment. The dotted lines represent Hamilton Harbour Remedial Action Plan (RAP) delisting objectives for dissolved oxygen (Cisco layer; 6 mg/l and 3 mg/l).

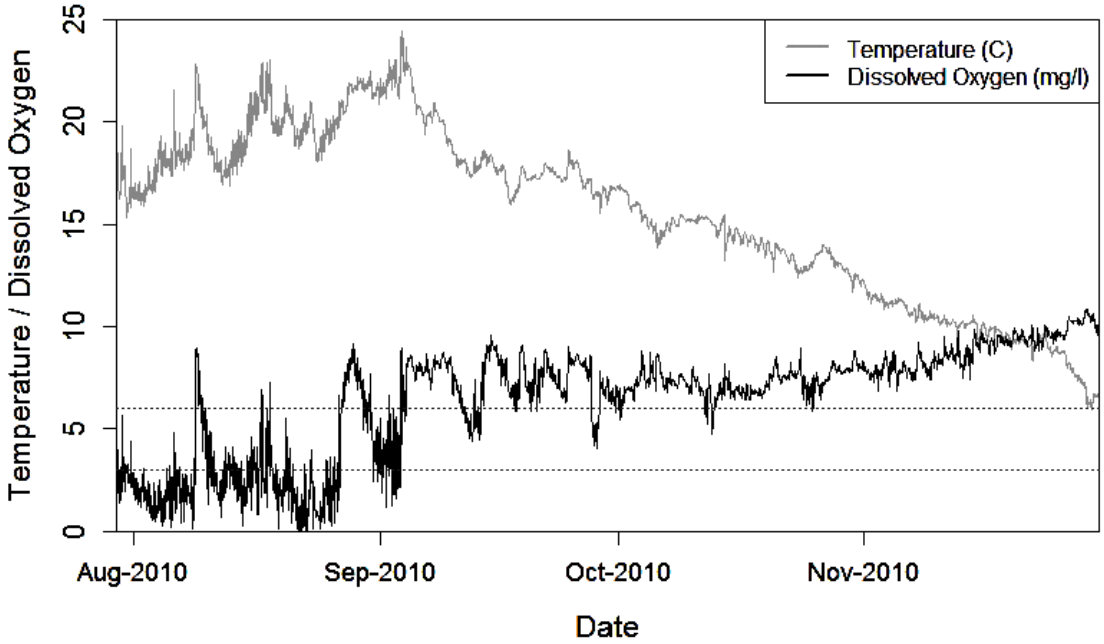

Figure 15. Long-term dissolved oxygen (mg/l) and temperature (ºC) deployment at STP from July 29, 2010 to November 30, 2010. The dotted lines represent Hamilton Harbour Remedial Action Plan (RAP) delisting objectives for dissolved oxygen (Cisco layer; 6 mg/l and 3 mg/l).

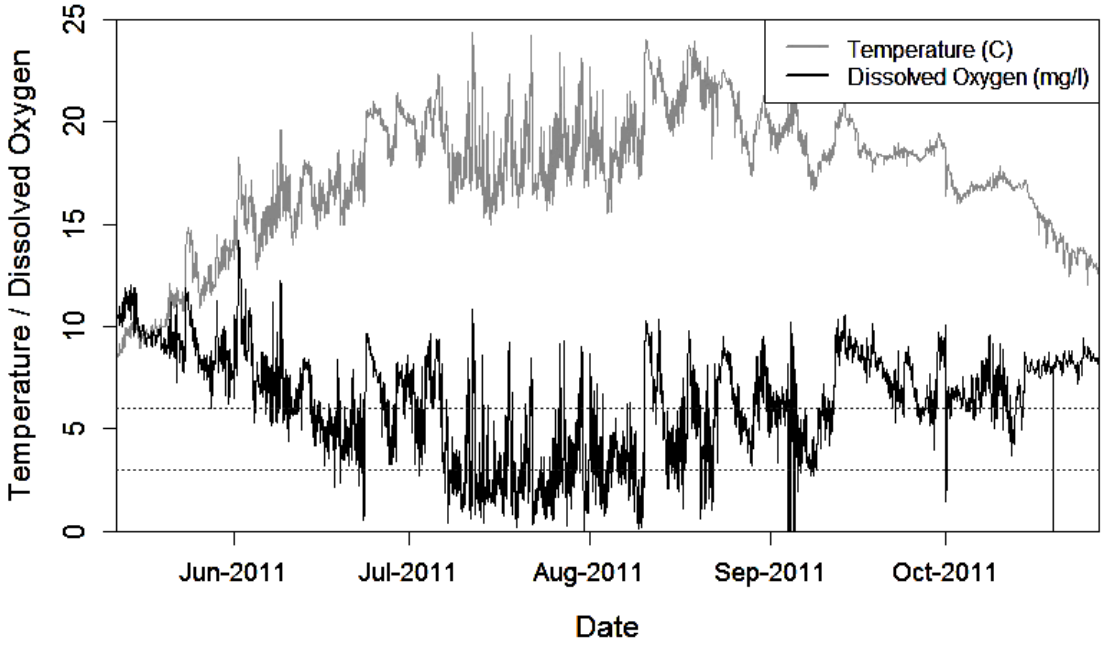

Figure 16. Long-term dissolved oxygen (mg/l) and temperature (ºC) deployment at STP from May 11, 2011 to October 27, 2011. Possible instrument failure near end of time series. The dotted lines represent Hamilton Harbour Remedial Action Plan (RAP) delisting objectives for dissolved oxygen (Cisco layer; 6 mg/l and 3 mg/l).

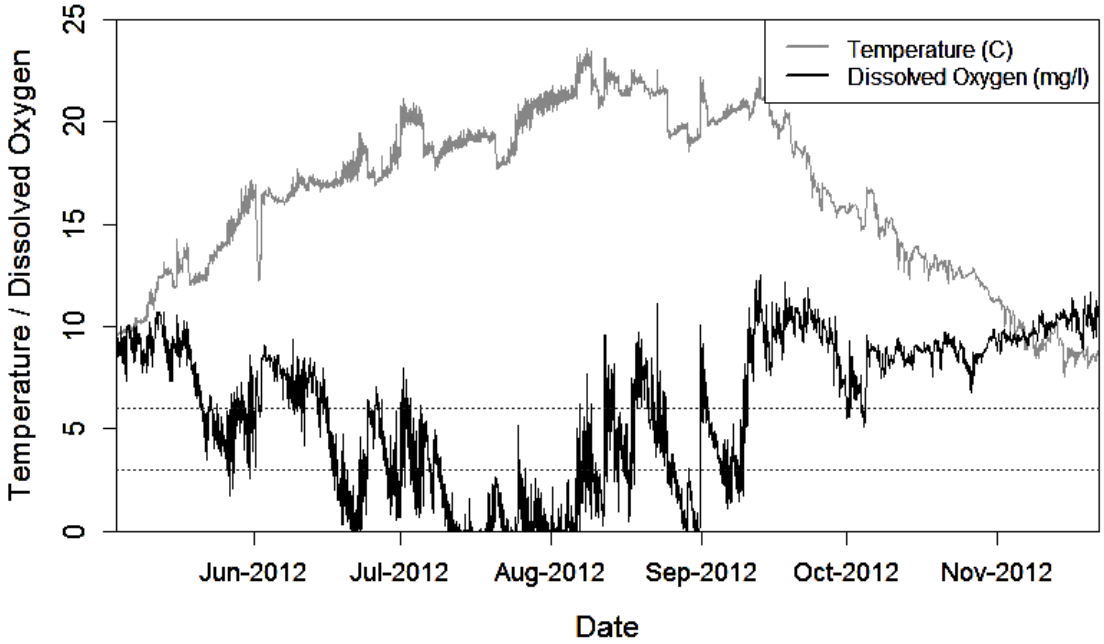

Figure 17. Long-term dissolved oxygen (mg/l) and temperature (ºC) deployment at STP from May 5, 2012 to November 21, 2012. The dotted lines represent Hamilton Harbour Remedial Action Plan (RAP) delisting objectives for dissolved oxygen (Cisco layer; 6 mg/l and 3 mg/l).

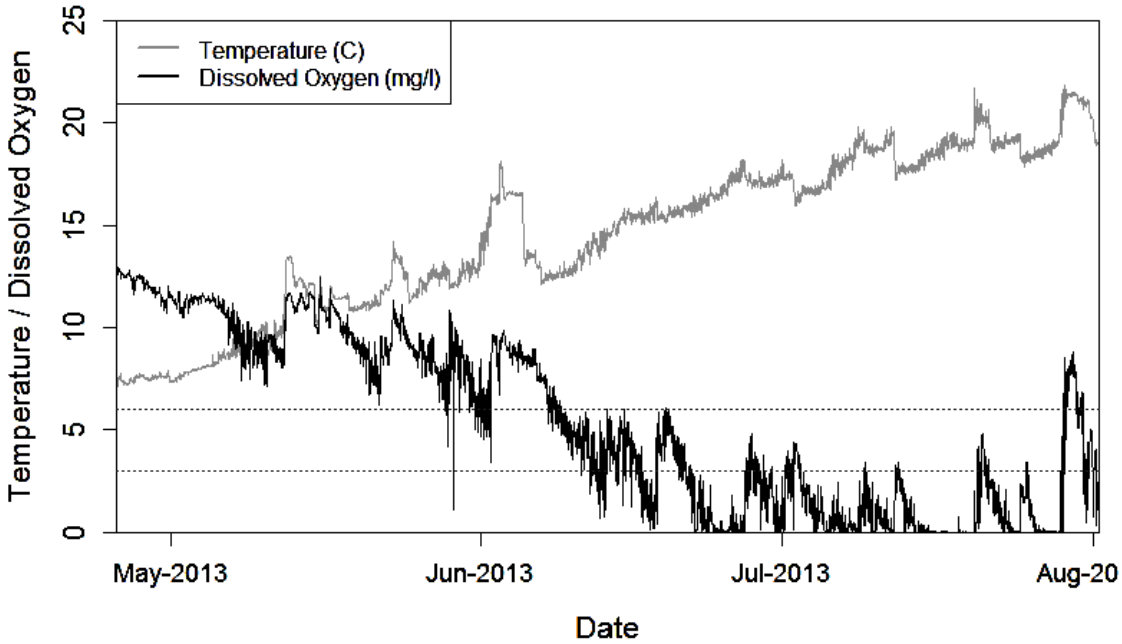

Figure 18. Long-term dissolved oxygen (mg/l) and temperature (ºC) deployment at STP from April 25, 2013 to August 1, 2013. The dotted lines represent Hamilton Harbour Remedial Action Plan (RAP) delisting objectives for dissolved oxygen (Cisco layer; 6 mg/l and 3 mg/l).

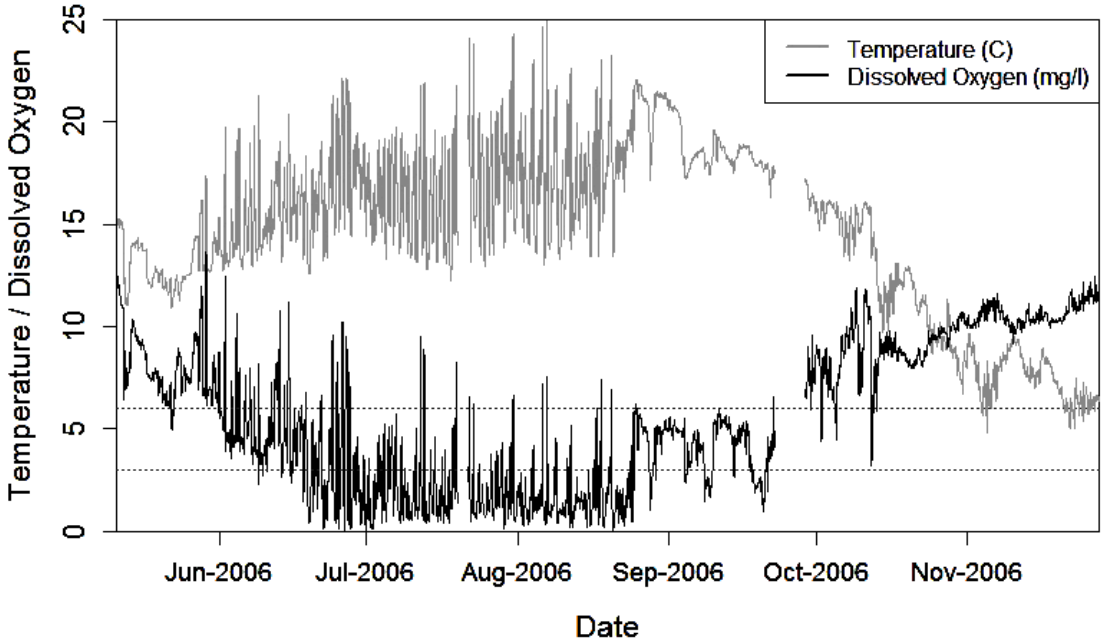

Figure 19. Long-term dissolved oxygen (mg/l) and temperature (ºC) deployment at West from May 10, 2006 to November 24, 2006. The dotted lines represent Hamilton Harbour Remedial Action Plan (RAP) delisting objectives for dissolved oxygen (Cisco layer; 6 mg/l and 3 mg/l).

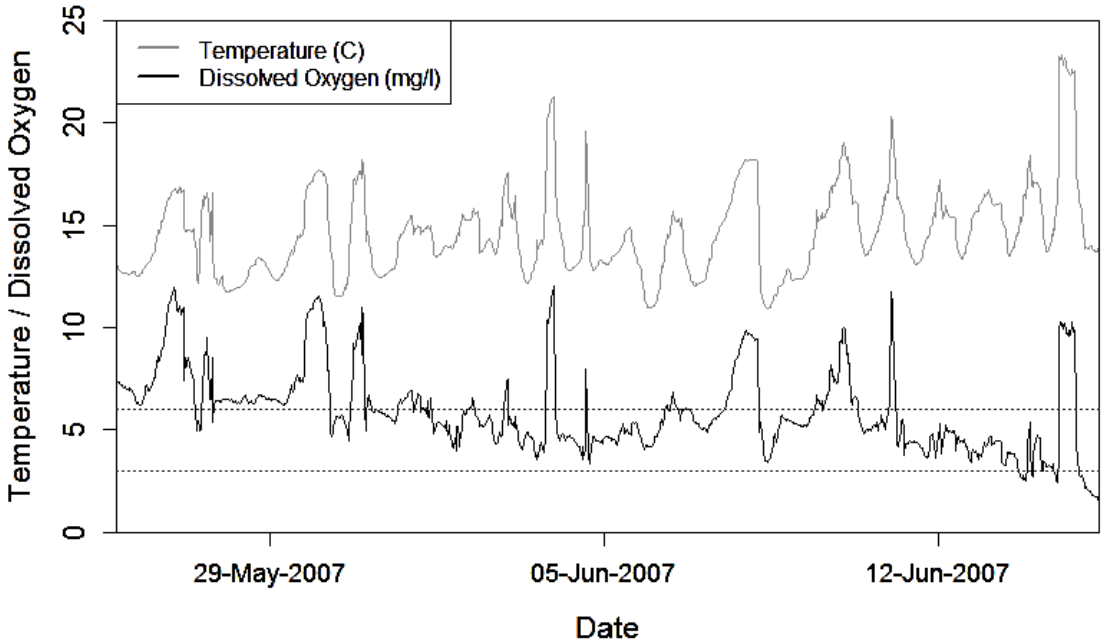

Figure 20. Long-term dissolved oxygen (mg/l) and temperature (ºC) deployment at West from May 25, 2007 to June 15, 2007. The dotted lines represent Hamilton Harbour Remedial Action Plan (RAP) delisting objectives for dissolved oxygen (Cisco layer; 6 mg/l and 3 mg/l).

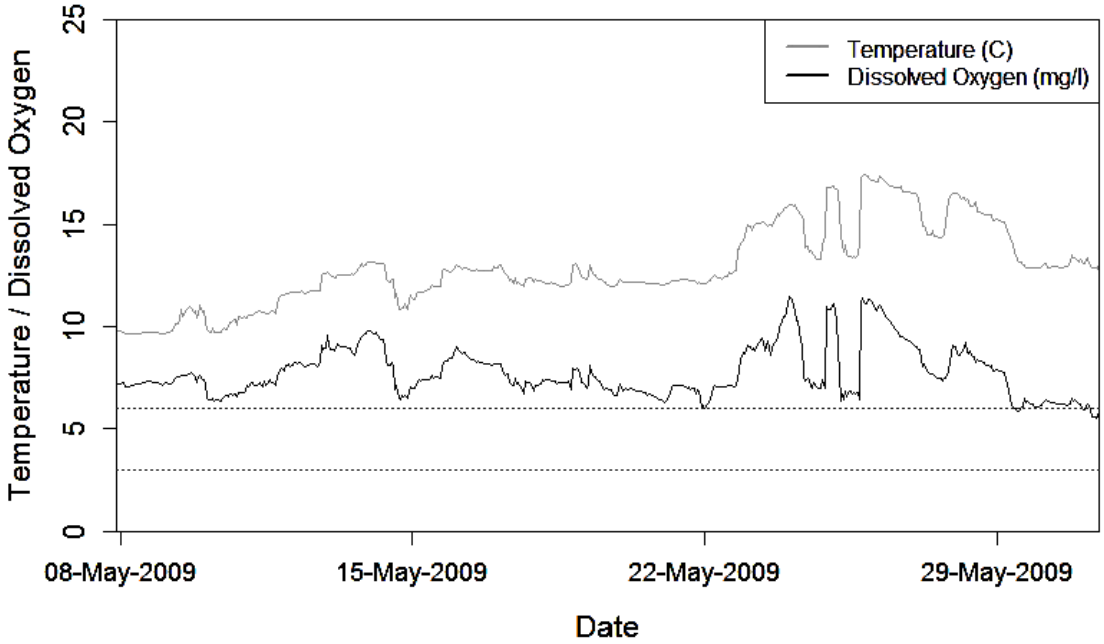

Figure 21. Long-term dissolved oxygen (mg/l) and temperature (ºC) deployment at West from May 7, 2009 to May 31, 2009. Possible instrument failure during deployment. The dotted lines represent Hamilton Harbour Remedial Action Plan (RAP) delisting objectives for dissolved oxygen (Cisco layer; 6 mg/l and 3 mg/l).

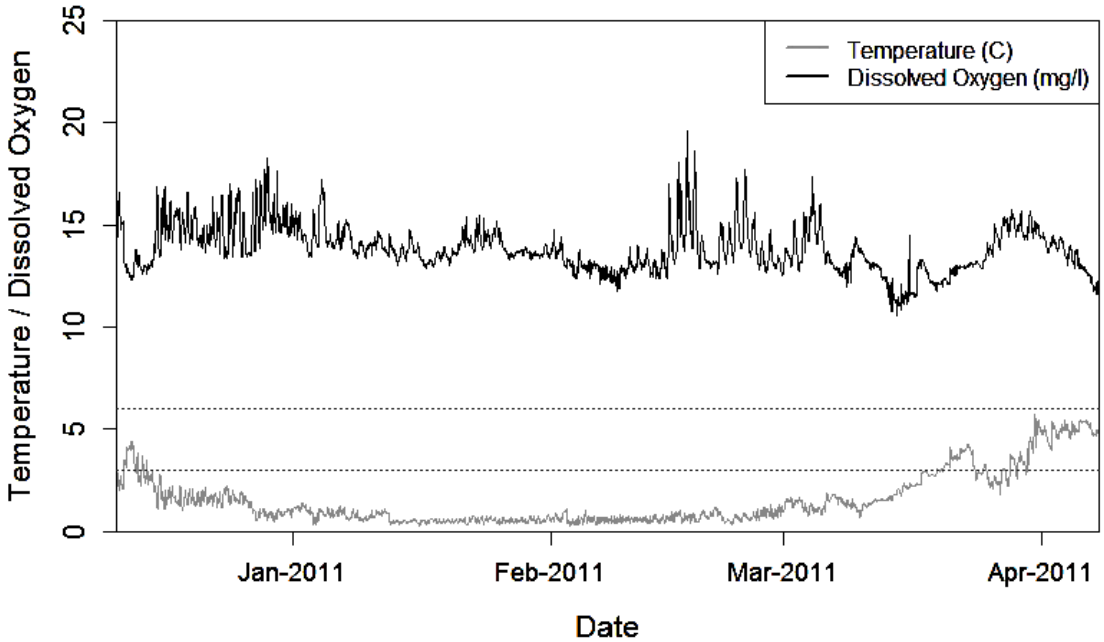

Figure 22. Long-term dissolved oxygen (mg/l) and temperature (ºC) deployment at West from December 10, 2010 to April 7, 2011. The dotted lines represent Hamilton Harbour Remedial Action Plan (RAP) delisting objectives for dissolved oxygen (Cisco layer; 6 mg/l and 3 mg/l).

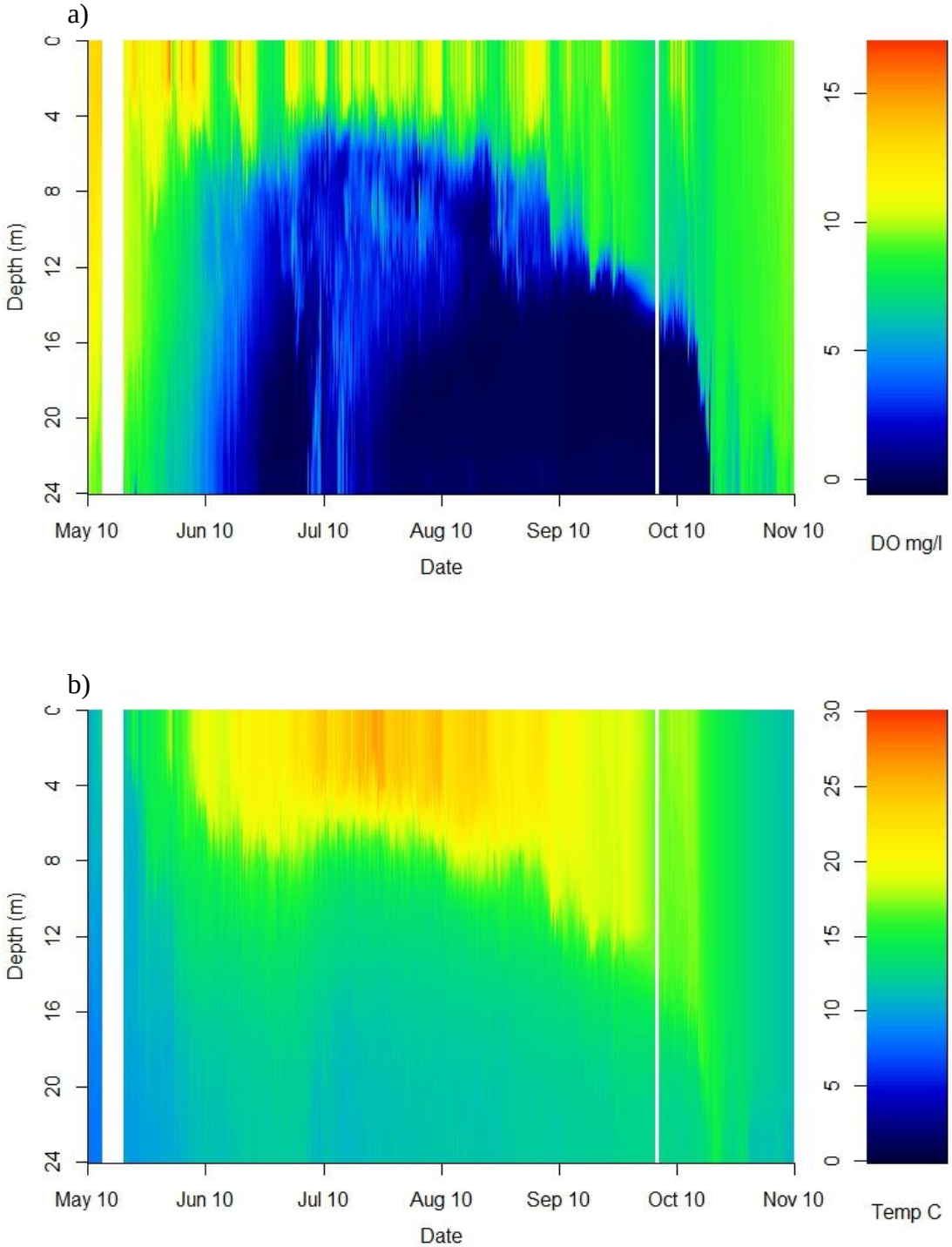

Figure 23. Profiler deployment at Centre station in 2011 showing a) dissolved oxygen (mg/l) and b) temperature (ºC) trends across the depth profile from May 10 to November 10, 2011. Periods where no data were recorded are in white.

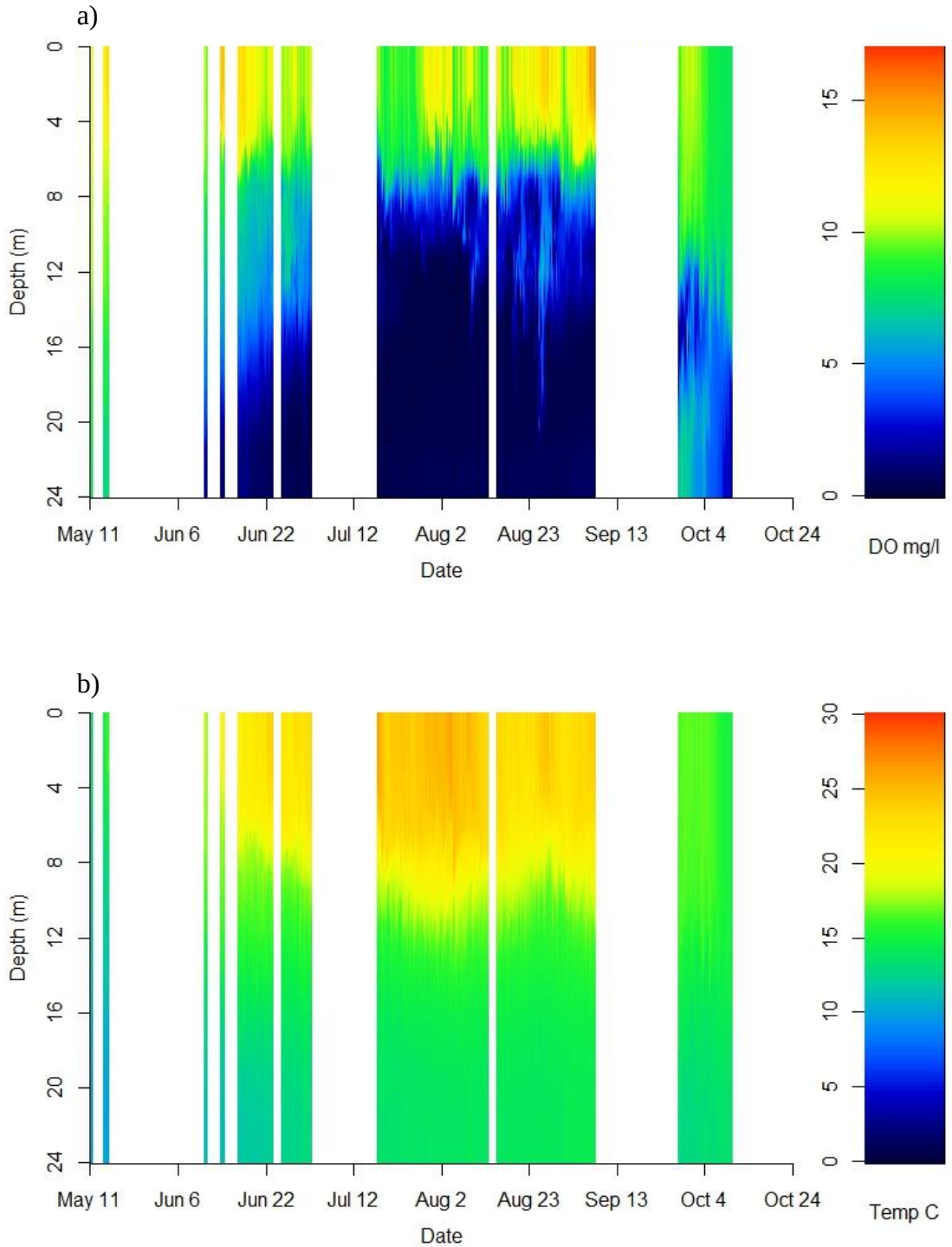

Figure 24. Profiler deployment at Centre station in 2012 showing a) dissolved oxygen (mg/l) and b) temperature (ºC) trends across the depth profile from May 11 to October 24, 2012. Periods where no data were recorded are in white.

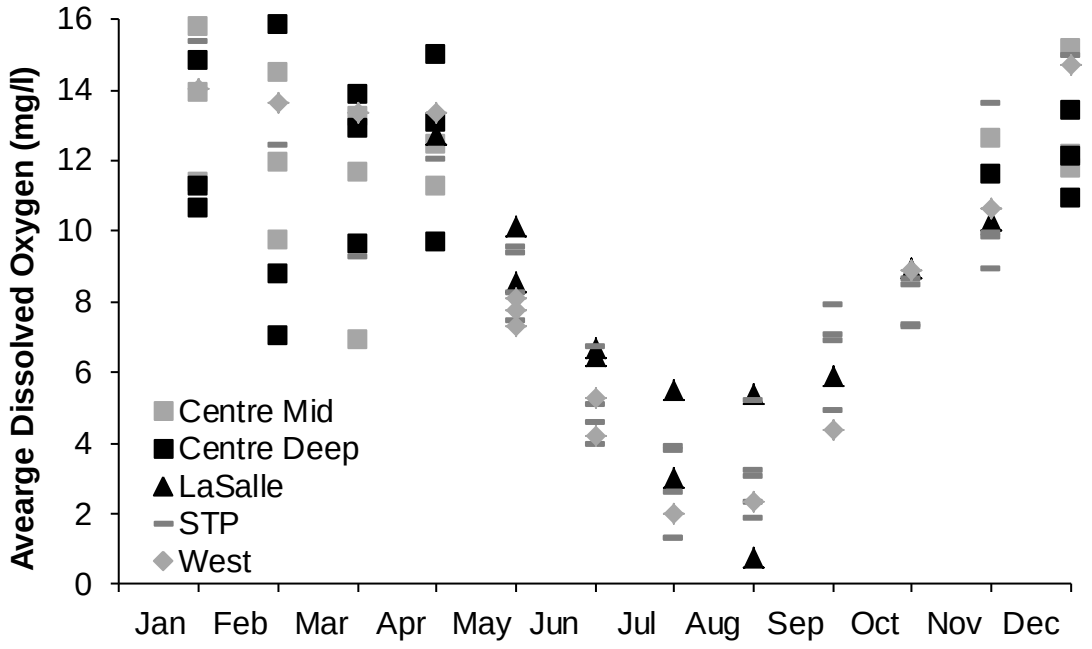

Figure 25. Average monthly dissolved oxygen by site for all months sampled with moored data loggers between 2006 and 2013.

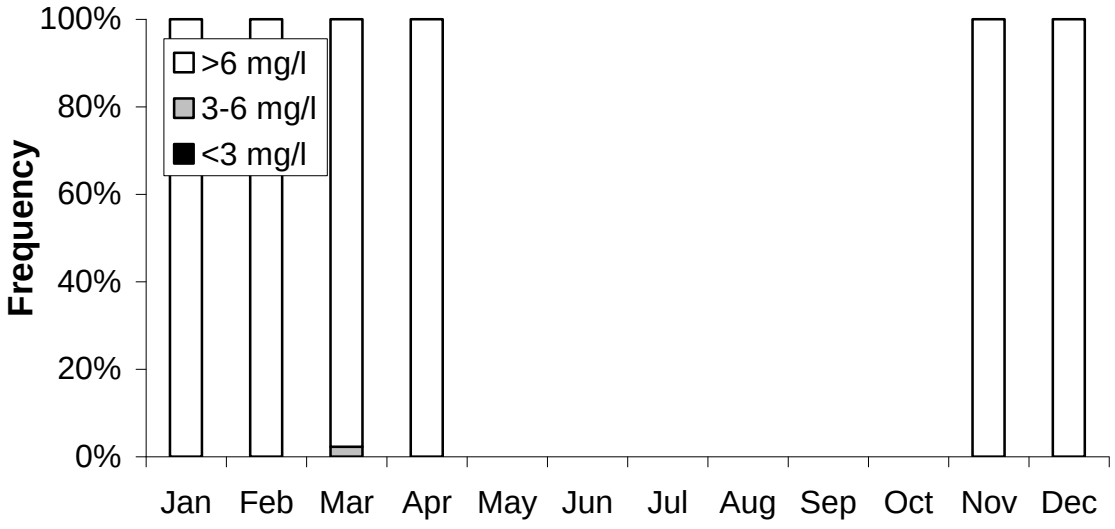

Figure 26. Proportion of time dissolved oxygen decreased below 6 and 3 mg/l at Centre-Mid station. Months are pooled across years. Months without bars represent periods where data meeting QA/QC standards were not collected.

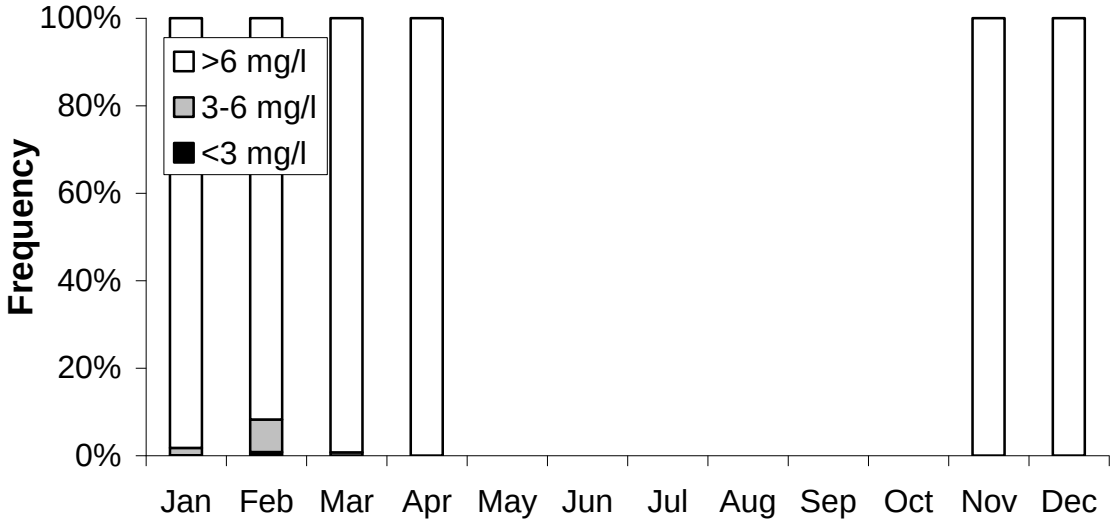

Figure 27. Proportion of time dissolved oxygen decreased below 6 and 3 mg/l at Centre-Deep station. Months are pooled across years. Months without bars represent periods where data meeting QA/QC standards were not collected.

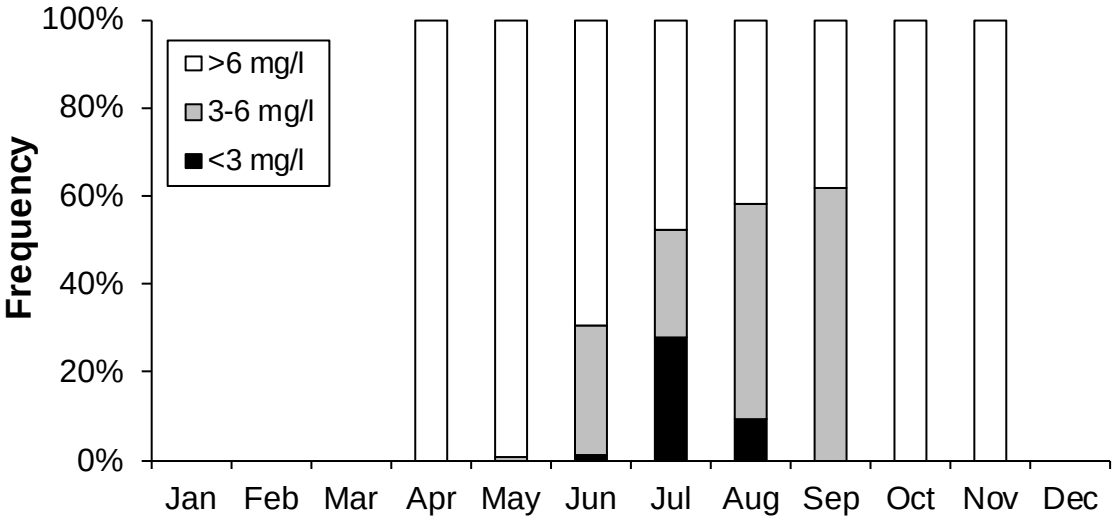

Figure 28. Proportion of time dissolved oxygen decreased below 6 and 3 mg/l at LaSalle station. Months are pooled across years. Months without bars represent periods where data meeting QA/QC standards were not collected.

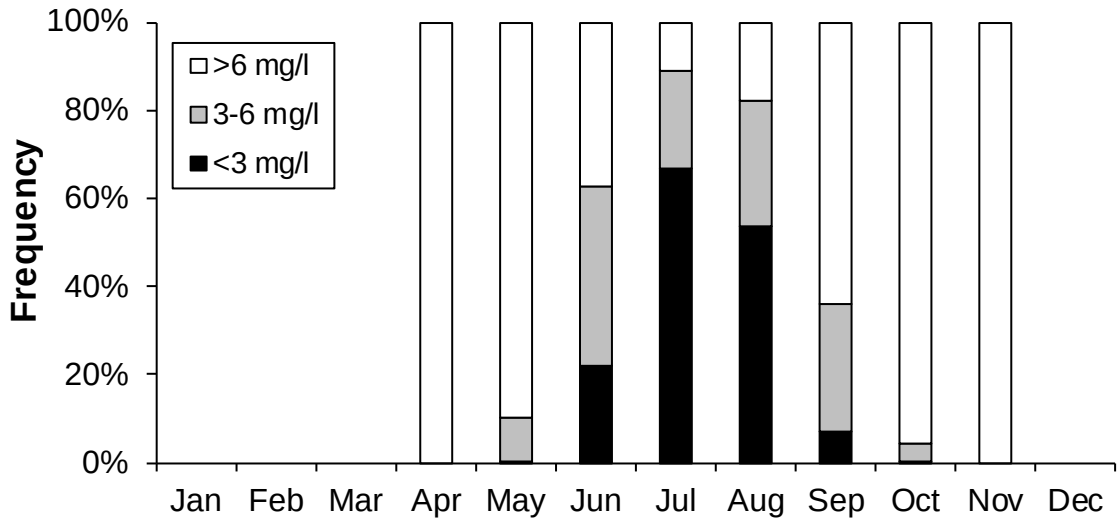

Figure 29. Proportion of time dissolved oxygen decreased below 6 and 3 mg/l at STP station. Months are pooled across years. Months without bars represent periods where data meeting QA/QC standards were not collected.

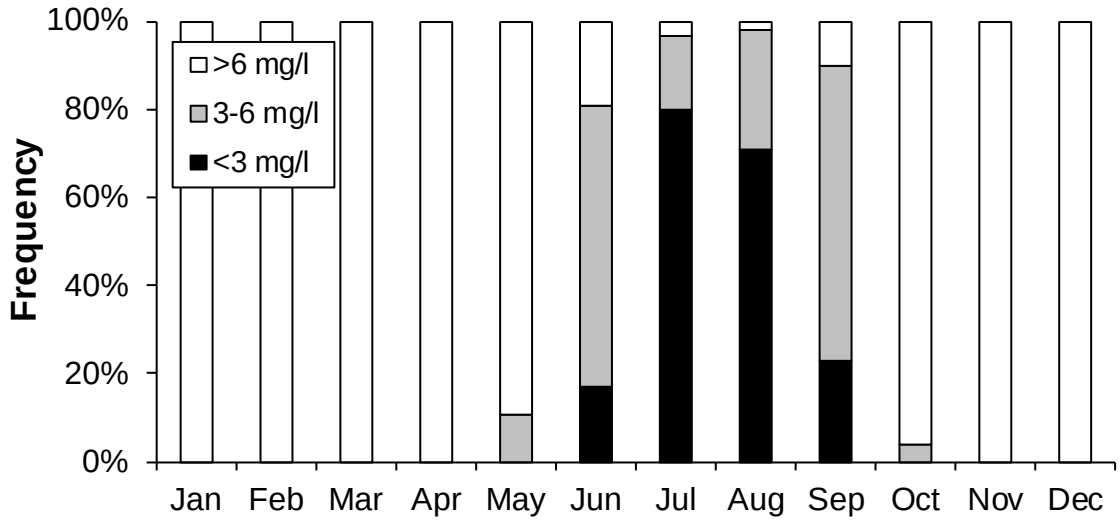

Figure 30. Proportion of time dissolved oxygen decreased below 6 and 3 mg/l at West station. Months are pooled across years. Months without bars represent periods where data meeting QA/QC standards were not collected.

lowest DO levels occurring in July at each station (Figure 28, 29, 30). Low DO conditions were more pronounced at STP (East) and West stations than at LaSalle (North). Typically, no long-term Hydrolab, YSI or HOBO loggers were deployed at the Centre station during the summer months, however the Profiler data shows dissolved oxygen depletion in the hypolimnion (Figures 23-24) through the summer stratification period and this validates the biweekly sampling of profile information gathered over a long period by environment Canada (Hiriaert-Baer et al. 2009). In general, the development of hypoxia at all coastal stations followed a normal depletion curve, with lowest values occurring in July and August when stratification was well-developed.

DISCUSSION

Information on dissolved oxygen dynamics is an important component of ecosystem and fish habitat assessments. As a part of the RAP assessments for the Hamilton Harbour AOC, a long-term DO data logging program was started in 2006 at four locations across the harbour. This program produced DO data for different parts of the harbour (Figure 1) at a finer time scale than previously collected. Data summaries for the monitoring program are provided in this report.

The long-term monitoring data presented in this report provide us with DO information across seasons and years, however they do not provide us with a complete picture of the harbour's DO regime. Sampling data across several seasons and sites is missing and the quality-assured data only extend over 56.6% of the time period sampled between May 2006 and August 2013 for the moored data. Furthermore, quality-assured data only extend over 96.6% and 50.1% of the time for the Profiler in 2011 and 2012, respectively. Nevertheless, the moored instrument data provided much more comprehensive knowledge of the long-term, fine interval (i.e. hourly) DO dynamics at several points near bottom than we had previously; although the long-term profile data collected weekly is invaluable. The Profiler data provided a wealth of information on DO dynamics vertically in the middle of the harbour at a finer interval (~3 times hourly) and allows us to visualize DO profile changes throughout the seasons, as the thermocline

developed and under periodic inundations from rivers and from Lake Ontario. Bi-weekly sampling that occurs at four stations in the harbour through the ice-free season (Hiriart-Baer et al. 2009) provides us with good knowledge of overall trends in dissolved oxygen but does not provide an indication of its variability at a finer time scale. *In situ* instrumentation is required to gather this information. Such details about temporal spatial dynamics are important for fishes as variability and frequency in DO has been observed to increase stress and reduce growth, affecting the degree to which fishes can tolerate low DO conditions (Chapman 1986) in general. Still, further modelling or interpolation of the long-term DO information is required to gain the spatial resolution needed for fish habitat assessments.

The current monitoring stations provide a good starting point in delineating the spatial extent of the hypoxic zones in the harbour. In this study, the DO monitoring stations were strategically selected and evenly distributed at varying depths across major zones in the harbour (Table 1; Figure 2). However, uncertainty exists in un-monitored zones between stations where changes in DO levels may occur at a finer spatial scale because of turbulent mixing. For example, coastal upwelling due to wind action may cause temperature and DO variability (Coman and Wells 2012).

In addition, the inflow and outflow exchange at the Burlington canal can also play a role in determining the DO levels in the harbour, and this location was not monitored specifically in this study. Ideally, additional monitoring stations may increase the spatial resolution of the data and also the interactions between major inflows and outflows of the Hamilton Harbour system. However, the cost of instrumentation and general maintenance of monitoring stations should be taken into account. Alternatively, DO levels can be interpolated using a temporal and spatial modelling approach taking into account a number of factors that affects DO levels in the harbour including phosphorus inputs and bio-oxygen demand (Kim et al. unpublished data). Nevertheless, capturing this finer level of detail may not be as important as capturing the major patterns, ranges, and levels of variability in DO dynamics at a reasonable resolution that is important for habitat

restoration as well as for predicting the dynamics of the ecosystem, fish communities and fish populations that are impaired.

The long-term deployment data in this study can be used in various ways, depending on RAP needs. For example, the histograms presented in Figures 26-30 provide the proportion of time the bottom waters of Hamilton Harbour may not be available throughout the year to fishes with low (>6 mg/l) or moderate (>3 mg/l) tolerances to low DO conditions. The detailed hourly figures show how variable water quality parameters can be on a short and medium time scales (e.g., Blukacz et al. 2009; Murphy et al. 2012). Techniques such as wavelet analysis could help untangle important patterns and change points in the DO variability observed (Blukacz et al. 2009).

There are a number of additional sources that can be used to help fill in any data gaps and to complement the current long-term monitoring data. Plans are in place to continue monitoring DO at three stations (LaSalle, STP and West) and add an additional station (Windemere) until 2015; this monitoring effort can fill in any seasonal gaps in knowledge across the harbour. Windermere Basin is an important addition to the monitoring program because it is considered one of the most impaired locations in the harbour due to its proximity to industrial and urban inputs, and it is likely that it will undergo significant change in the near future after remediation efforts, including the removal of contaminated inputs and STP upgrades to tertiary treatment. Additional information on general long-term DO trends may be gained through Environment Canada, where DO profiles have been taken bi-weekly throughout the ice-free season at the Centre station since 1987, and at the four ‘corners’ of the harbour, including Windermere Basin, since 2007 (Hiriart-Baer et al. 2009).

Currently, hydrodynamic DO models for Hamilton Harbour are under development in collaboration with the ecological and physical modelling laboratories at the University of Toronto. The project's aim is to develop robust predictive tools for DO based on the long-term monitoring trends in this study and biophysical forcing. One method employs a Bayesian kriging approach accounting for sediment oxygen demand,

nutrient inputs and a coarse spatial segmentation of the harbour (Kim et al. unpublished data). Another hydrodynamic method will predict the intermittently hypoxic zone at mid-depths, and possibly up to the coasts, in the harbour.

Long-term DO data and model output will be incorporated into fish habitat assessments under the RAP BUI #14 "Fish and Wildlife Habitat." The synthesized dissolved oxygen data will be integrated with other habitat information (Doolittle et al. 2010) and fish-habitat associations in models of fish habitat supply (e.g. Minns et al. 2001). Assessments will determine the amount and quality of habitat available to various fish guilds through the year. Given that fish species in Hamilton Harbour (Bowlby et al. 2010) have different DO needs, the fish community will be divided into dissolved oxygen guilds based on a comprehensive literature review of DO tolerances (Neigum et al. unpublished data). Results from the assessment will feed into the RAP Stage 3 report to assess the historical, current and future status of fish habitat in Hamilton Harbour.

ACKNOWLEDGEMENTS

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