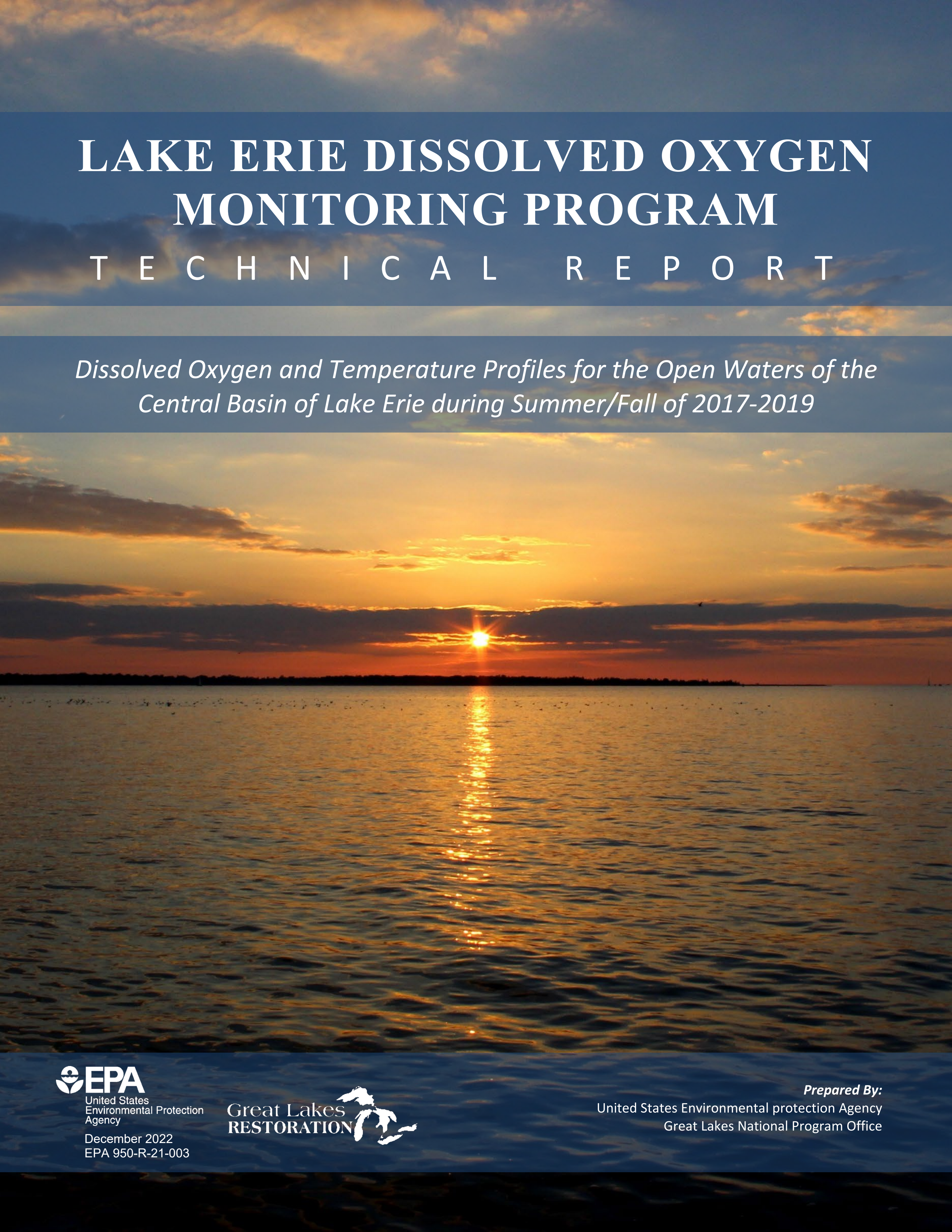

LAKE ERIE DISSOLVED OXYGEN MONITORING PROGRAM

TECHNICAL REPORT

Dissolved Oxygen and Temperature Profiles for the Open Waters of the Central Basin of Lake Erie during Summer/Fall of 2017-2019

United States
Environmental Protection
Agency
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Great Lakes
RESTORATION

Prepared By:
United States Environmental protection Agency
Great Lakes National Program Office

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Cover photo: Sunset over Lake Erie. Photo by Katiefish via Pixabay

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1. EXECUTIVE SUMMARY

The United States Environmental Protection Agency (EPA) Great Lakes National Program Office (GLNPO) Lake Erie Dissolved Oxygen Monitoring Program monitors the oxygen and temperature profiles at 10 fixed stations in the central basin of Lake Erie during the stratified season to assess water quality trends and measure progress made in achieving water quality improvements.

Hypoxic and anoxic conditions (< 2 mg O_2/L and < 1 mg O_2/L, respectively) were observed in all three sampling seasons (2017-2019) by our ship-based observations of dissolved oxygen (DO) concentrations. However, seasonal variations can cause annual differences in the onset, extent and duration of these low-oxygen conditions in a given year. For example, 2017 had one of the higher annual DO depletion rates observed in the last two decades, which led to the presence of anoxic conditions much earlier in the season than on average over the time series. On the other hand, 2018 and 2019 exhibited two of the lowest DO annual depletion rates, and anoxia was not seen until almost a month later during these seasons. Seasonal synopses for 2017-2019 are as follows:

During the course of the 2017 sampling season (June 8 – October 3):

- Six surveys were conducted during the 2017 field season using the EPA R/V *Lake Guardian*. Four additional surveys were conducted using the USGS R/V *Muskie.*
- Surface water temperatures increased from 14.0 °C to 19.7 °C, while hypolimnion temperatures increased from 9.8 °C to 13.9 °C.
- Hypolimnion DO concentrations during the sampling season decreased from approximately 9.2 mg O_2/L to 0.04 mg O_2/L.
- Low-oxygen conditions (< 6 mg O_2/L) were first recorded at one station on June 27, 2017.
- Hypoxic and anoxic conditions were first recorded during the August 13-14, 2017 survey. Hypoxia was present at two stations, while anoxia was present at an additional seven stations.
- The annual corrected oxygen depletion rate was 3.71 mg O_2/L/month.

During the course of the 2018 sampling season (June 7 – October 3):

- Six surveys were conducted during the 2018 field season using the EPA R/V *Lake Guardian*. Two additional surveys were conducted using the USGS R/V *Muskie.*
- Surface temperatures during the field season increased from 14.1 °C to 24.0 °C, while hypolimnion temperatures increased from 8.2 °C to 12.4 °C.
- Hypolimnion DO concentrations during the field season decreased from approximately 11.9 mg O_2/L to 0.12 mg O_2/L.
- Low-oxygen conditions (< 6 mg O_2/L) were first recorded at four stations on July 19, 2018.
- Hypoxic and anoxic conditions were first recorded during the September 6, 2018 survey. Hypoxia was present at two stations, while anoxia was present at one additional station.
- The annual corrected oxygen depletion rate was 2.88 mg O_2/L/month.

During the course of the 2019 sampling season (June 5 – October 8):

- Five surveys were conducted during the 2019 field season using the EPA R/V *Lake Guardian*. Four additional surveys were conducted using the USGS R/V *Muskie.*
- Surface water temperatures increased from 12.3 °C to 23.5 °C, while hypolimnion temperatures increased from 7.8 °C to 14.5 °C.
- Hypolimnion DO concentrations during the sampling season decreased from approximately 9.8 mg O_2/L to 0.10 mg O_2/L.
- Low-oxygen conditions (< 6 mg O_2/L) were first recorded at five stations on July 17, 2019.
- Hypoxic and anoxic conditions were first recorded during the August 26, 2019 survey. Hypoxia was present at two stations, while anoxia was present at one additional station.
- The annual corrected oxygen depletion rate was 2.87 mg O_2/L/month.

2. INTRODUCTION

Lake Erie has been severely impacted by excessive anthropogenic loadings of phosphorous resulting in abundant algal growth and is a factor that contributes to dissolved oxygen (DO) depletion in the bottom waters of the central basin. Total phosphorus loads to Lake Erie reached their peak in the late 1960s and early 1970s with annual loads in excess of 20,000 metric tonnes per annum (MTA) (Maccoux et al., 2016). In 1978, Canada and the United States signed an amendment to the 1972 Great Lakes Water Quality Agreement (GLWQA) that sought to reduce total phosphorus loads to Lake Erie to 11,000 MTA. In order to determine if the areal extent or duration of the oxygen-depleted area was improving or further deteriorating, annual monitoring of the water column for thermal structure and DO concentration was needed throughout the stratified season. The U.S. Environmental Protection Agency (EPA) Great Lakes National Program Office (GLNPO) established the Lake Erie Dissolved Oxygen Monitoring Program in 1983. This program was designed to collect necessary DO concentration data to calculate an annual normalized rate of DO depletion in the central basin of Lake Erie. Additionally, these data could be used by federal and state water quality agencies to assess the effectiveness of phosphorus load reduction programs.

Numerous phosphorus reduction programs were implemented in support of the GLWQA, and by the early 1980s, the annual phosphorus load to Lake Erie had been reduced to near targeted amounts (Dolan, 1993). Correspondingly, the load reduction resulted in the decrease of the total area affected by low oxygenated waters (Makarewicz and Bertram, 1991). By the mid-1990s, the total extent of the hypoxic area (DO levels < 2 mg/L) had decreased such that the total impacted area was smaller in area than had been observed in previous decades. However, by the 2000s the annual extent of area affected by hypoxia had increased, returning to the larger areal extent seen in the late 1980s (Zhou et al., 2013). The annual average hypoxic area in the central basin since the early 2000s is approximately 4,500 km^2 (1,737 mi^2) (U.S.EPA, 2018), while the largest hypoxic extent recorded in the past decade – 8,800 km^2 (3,398 mi^2) – occurred in 2012, following the record-setting algal bloom in 2011 (U.S. EPA, 2018). Hypoxia in Lake Erie reduces habitat and food supply for fish and complicates drinking water treatment (Rowe et al. 2019).

In 2012, the GLWQA was updated to enhance water quality programs that ensure the “chemical, physical and biological integrity” of the Great Lakes (Canada and United States, 2012). As part of Annex 4 (Nutrients Annex) of this agreement, the governments of the United States and Canada adopted the following Lake Ecosystem Objectives:

- minimize the extent of hypoxic zones in the waters of the Great Lakes associated with excessive phosphorus loading, with particular emphasis on Lake Erie;
- maintain the levels of algal biomass below the level constituting a nuisance condition;
- maintain algal species consistent with healthy aquatic ecosystems in the nearshore Waters of the Great Lakes;
- maintain cyanobacteria biomass at levels that do not produce concentrations of toxins that pose a threat to human or ecosystem health in the Waters of the Great Lakes;
- maintain an oligotrophic state, relative algal biomass, and algal species consistent with healthy aquatic ecosystems, in the open waters of Lakes Superior, Michigan, Huron and Ontario; and
- maintain mesotrophic conditions in the open waters of the western and central basins of Lake Erie, and oligotrophic conditions in the eastern basin of Lake Erie.

GLNPO continues to monitor the thermal structure and DO concentrations in the central basin of Lake Erie throughout the stratified season each year. The ongoing monitoring ensures that data are available to assess the objectives put forth in the GLWQA, and also allow for the evaluation of status and trends over time. This report summarizes the results of the 2017, 2018, and 2019 Lake Erie Dissolved Oxygen Monitoring Program surveys and places those results within the context of historical data.

3. METHODS

Annually, 10 fixed stations (Figure 1) in the offshore waters of the central basin are sampled at approximately 3-week intervals, during the stratified season (June-October). Sampling usually begins in early June, when the water column begins to stratify, or separate, into a warmer upper layer (epilimnion) and a cooler bottom layer (hypolimnion) and typically concludes in late September to mid-October just before the water column seasonally destratifies, or "turns over," and assumes a uniform temperature profile. The EPA R/V *Lake Guardian* is used as the sampling platform whenever scheduling and other operating constraints permit. In the event that the R/V *Lake Guardian* is not available for one or more scheduled sampling times, or additional surveys are scheduled, alternate vessel support is used to conduct the sampling. The USGS R/V *Muskie* was used to conduct 10 additional surveys during 2017-2019 (four surveys in 2017, two in 2018 and four in 2019). At each station visit, the thermal structure of the water column is recorded by an electronic profiling CTD (Conductivity, Temperature, Depth (pressure) sensor) while DO concentrations are measured and recorded by an additional oxygen sensor integrated into the CTD instrument package. For all three years, a SeaBird Scientific SBE 911plus CTD and SBE 19plus V2 SeaCAT Profiler CTD were used for collecting water temperature data, and a SBE43 Dissolved Oxygen Sensor integrated into each of the SBE CTDs was used for collecting DO data. Comparison analyses using the standard Quality Control (QC) criteria for the DO program are conducted to ensure comparable data are being collected between different instrumentation whenever more than one SBE CTD is used during a given season. Samples from each instrument are assessed. The resulting temperature and DO depth profiles, which provide a visual display of the thermal structure and DO content of the water (Figure 2), are used to calculate the annual DO depletion rate (U.S. EPA, 2018).

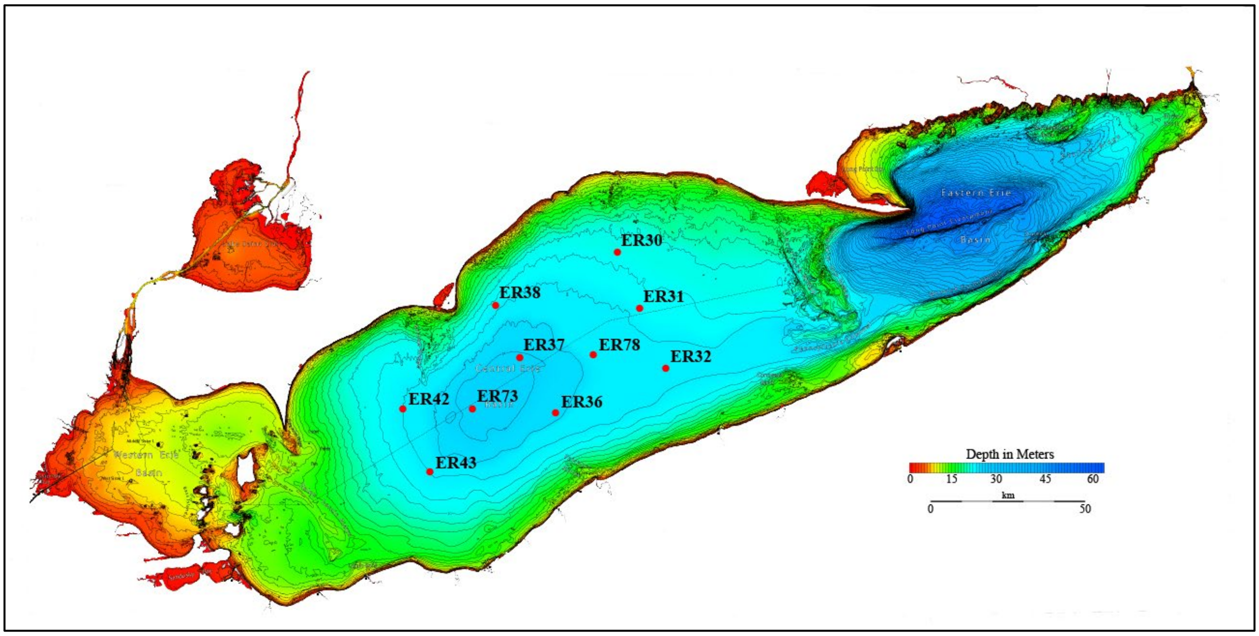

Figure 1. Map of GLNPO dissolved oxygen (DO) monitoring stations in the central basin of Lake Erie.

Quality Assurance samples are collected at two of the 10 stations during each survey and used to confirm the accuracy of the sensor measurements. DO measurements from the sensor are compared to those determined by the Winkler micro-titration method (U.S. EPA, 2018) for water samples collected at 2 meters below the surface and at 1 meter above the lake bottom. Temperature measurements from the sensor are compared to surface water thermometer readings obtained from the hull-mounted transducer on the research vessel.

In 2017, additional Winkler titration and temperature measurements were collected during several surveys as part of a separate project. These supplementary samples were also included as QC samples for this year.

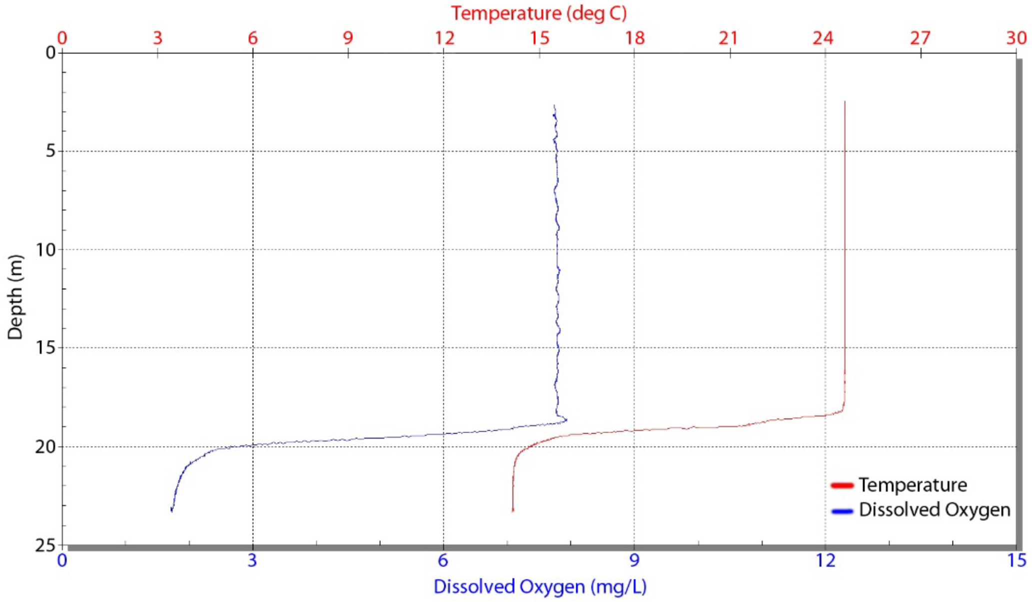

Figure 2. Example of a temperature and DO depth profile from Lake Erie central basin in late summer.

After each survey, water temperature and DO concentration data from the CTDs are averaged for the epilimnion and hypolimnion. A grand mean of hypolimnion DO concentration is calculated for each station to generate a map of bottom DO concentrations for the central basin of Lake Erie at the time of sampling.

To reduce the amount of inter-annual variability in DO data from Lake Erie, an annual corrected oxygen depletion rate is calculated using a Microsoft Access program (LakeErieDOv05.mdb). This software statistically adjusts the data for vertical mixing and seasonable variability and normalizes it to a constant temperature and hypolimnion thickness according to the procedures used by Rosa and Burns (1987). The resultant or "corrected" annual rate of DO depletion (mg O_2/L/month) is artificial for any given year, but permits the identification of time trends with more precision.

For comparisons between years, results over a 10-year period (2008-2017, 2009-2018 and 2010-2019) were compared statistically using a general linear model (GLM) approach to test whether there is a significant difference in the relationship between time (expressed as Julian day minus 150 to place the y-intercept near the beginning of the sampling period; referred to as SurveyDay in Table 5) and either hypolimnion temperature, thickness or DO concentration (Tables 5a-5i). This approach assumes a constant rate of change per day in the unadjusted measurements (i.e., hypolimnion temperature, thickness and DO) over the full June to October sampling period within each year, which differs slightly from the Rosa and Burns (1987) method that only assumes a constant rate of change between sampling events, but not across the entire sampling period. The GLM model includes a separate factor for the sampling year, and a Julian day x year interaction term, which is used to test whether the rate of change in the hypolimnion temperature, thickness or DO varies significantly between years (i.e., whether the estimated slope varies between years). Statistical significance of the GLM model tests was set at alpha=0.05. Statistical analysis was performed using the GLM procedure in SAS Version 9.4 (SAS Institute, Cary, NC).

4. QUALITY ASSURANCE AND QUALITY CONTROL

GLNPO's DO monitoring surveys operate under an approved Quality Management Plan, a Quality Assurance Project Plan (QAPP), and standard operating procedures (U.S. EPA, 2020). The 2017 surveys operated under Revision 10 of the QAPP (U.S. EPA, 2017), and the 2018 and 2019 surveys operated under Revision 11 of the QAPP (U.S. EPA, 2018). The overall data quality objective for this project is to acquire measurements of DO and temperature at the central basin stations in Lake Erie that are representative of the actual conditions present at the time of sampling.

Acceptance criteria for DO and temperature (Table 1) are based on the Relative Percent Difference (RPD) between two independently derived measurements. By definition, RPD is the difference between two measurements divided by the average of both and expressed as a percent value.

The accuracy criteria for acceptable DO measurements is an RPD of 10% between sensor and averaged Winkler values, or an absolute difference between measurement methods of 0.5 mg/L when DO concentrations are less than 5 mg/L. A maximum RPD of 2% is the acceptable accuracy for water temperature. Acceptable levels of precision are defined as a maximum difference of 0.2 mg/L between Winkler replicates and agreement within 5% between sensor measurements for DO. Acceptable precision for water temperature was defined as agreement within 2% between sensor measurements.

Table 1. Acceptance criteria for DO and temperature data

Parameter	Accuracy criteria	Precision criteria
Temperature	2% RPD	• 2% between sensor measurements
Dissolved oxygen (≥ 5 mg/L)	10% RPD	• 0.2 mg/L between Winkler replicates • 5% between sensor measurements
Dissolved oxygen (< 5 mg/L)	0.5 mg/L absolute difference	

For this project, completeness is the measure of the number of samples obtained compared to the amount that was expected to be obtained under normal conditions. The completeness goal is to obtain DO and temperature profiles within accuracy and precision limits at 90% of all designated stations during each survey.

5. RESULTS AND DISCUSSION

2017 Synopsis

During the first survey (June 8, 2017), all stations were stratified with an average temperature difference of 4.2 °C between the epilimnion and hypolimnion layers (Table 2). Over the sampling season, average temperatures increased in the epilimnion from 14.0 °C to 19.7 °C and in the hypolimnion from 9.8 °C to 13.9 °C. Average DO concentrations during the sampling season decreased from 10.3 mg O_2/L to 8.0 mg O_2/L in the epilimnion and from 9.2 mg O_2/L to 0.04 mg O_2/L in the hypolimnion.

Low DO concentrations (< 6 mg O_2/L) in the hypolimnion were first detected at the south, western-most sampling station (ER43) during the late June cruise. By late July, all stations had DO concentrations below 6 mg O_2/L and by mid-August, seven stations had become anoxic (< 1 mg O_2/L). During mid-September and early October all stations that had a hypolimnion present were experiencing anoxic conditions (Figure 3).

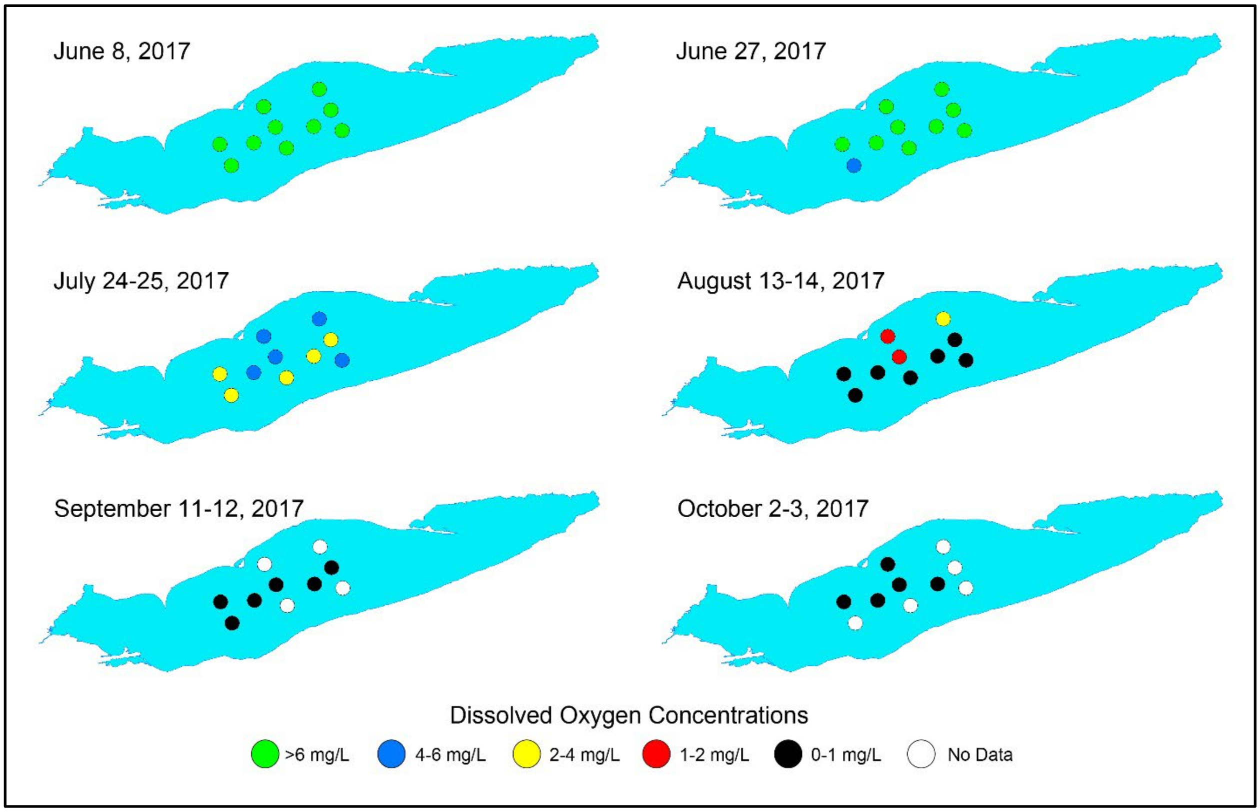

Figure 3. 2017 station means for hypolimnion DO concentrations in the central basin of Lake Erie.

Table 2. Mean water temperature (± SD) and DO for each survey in 2017.

2017 Survey dates	CTD used	Stations (#)	Epilimnion		Hypolimnion		
			Temperature (°C)	DO (mg/L)	Temperature (°C)	DO (mg/L)	Thickness (m)
June 8	SBE 911+	10	14.04 ± 0.52	10.34 ± 0.11	9.81 ± 0.26	9.20 ± 0.55	6.24 ± 1.60
June 27	SBE 911+	10	18.45 ± 1.09	9.53 ± 0.20	10.56 ± 0.20	7.96 ± 1.20	6.74 ± 1.88
July 24-25	SBE 911+	10	21.68 ± 0.85	8.54 ± 0.24	11.95 ± 1.18	3.87 ± 1.20	4.91 ± 2.32
August 13-14	SBE 911+	10	21.68 ± 1.19	8.29 ± 0.54	13.04 ± 1.54	0.96 ± 1.07	3.22 ± 1.92
September 11-12	SBE 911+	6	19.61 ± 0.32	8.62 ± 0.21	12.82 ± 1.11	0.04 ± 0.01	3.72 ± 2.17
October 2-3	SBE 911+	5	19.69 ± 0.22	7.98 ± 0.24	13.86 ± 1.24	0.09 ± 0.11	2.07 ± 0.62

Two reoccurring data quality issues were present during the 2017 sampling season (Table A-1). The temperature accuracy checks exceeded the acceptance criteria for 27% of the samples collected. Additionally, the temperature values from the hull-mounted transponder were higher than the CTD temperature values for 34 of the 44 readings (which includes all but one of the samples that exceeded the QC criteria). Heat transfer from the hull to the surrounding water may be one cause of this general bias seen in the data. As such, this thermometer may not be an appropriate instrument for assessing the accuracy of the CTD temperature values. Therefore, an independent temperature sensor was used during the 2018 sampling season to collect temperature values to assess whether the high exceedance rate for temperature accuracy was associated with the hull transducer or an issue with the CTD (e.g., calibration factor, sensor).

Winkler precision checks exceeded the acceptance criteria for nearly 30% of the samples collected. However, 96% of the Winkler-CTD accuracy checks for values above 5.0 mg/L were still within acceptance criteria (Appendix A). Inexperienced technicians or improper laboratory procedures may have contributed to the high exceedance rate in 2017. As such, additional training and/or a longer observational period will be required for any inexperienced individual planning to participate in a DO survey during that year.

2018 Synopsis

During the first survey (June 7-8, 2018), all stations were stratified with an average temperature difference of 5.9 °C between the epilimnion and hypolimnion layers (Table 3). By the late September survey, the hypolimnion was so thin that only the deepest portion of the basin still had distinct water layers. As such, hypolimnion conditions could only be measured at the five southern and southeastern stations during this survey and the following survey in early October. During the sampling season, average temperatures increased in the epilimnion from 14.1 °C to 24.0 °C by mid-August, before decreasing to 19.2 °C by early October. Average temperatures in the hypolimnion increased from 8.2 °C to 12.6 °C. Average DO concentrations during the sampling season decreased from 11.2 mg O_2/L to 7.9 mg O_2/L in the epilimnion and from 11.9 mg O_2/L to 0.12 mg O_2/L in the hypolimnion.

Low-oxygen concentrations (< 6 mg O_2/L) in the hypolimnion were first detected at the north and western-most sampling stations (ER30, ER38, ER42 and ER43) during the mid-July cruise. The first station to become anoxic (< 1 mg O_2/L) was observed during the early-September survey, and by early-October all stations that had a hypolimnion present were experiencing anoxic conditions (Figure 4).

Winkler precision checks exceeded the acceptance criteria for approximately 27% of the samples collected (Appendix A). However, all Winkler-CTD accuracy checks for values above 5.0mg/L were within acceptance criteria.

In response to the data quality issues observed in 2017 associated with the temperature sensors, an independent handheld thermometer was used instead of the hull-mounted transducer for the QC checks during this year. This method reduced the overall bias seen with the hull-mounted transducer (75% of all samples in 2017 had a negative relative percent difference versus 45% in 2018). However, this method does not appear to be a completely viable solution to this ongoing issue. Because this new probe was lightweight and on the end of a long cable, any surface current or movement of the vessel made it increasingly difficult for the sensor to sink to the same depth as the CTD temperature sensor (in some instances greater than 2 meters depth). As such, the two sensors were often not sampling at the same depth. Any temperature gradient in these surface waters might therefore result in an exceedance of the QC criteria simply due to position in the water column, instead of any problems with the sensors or their calibrations (Appendix A).

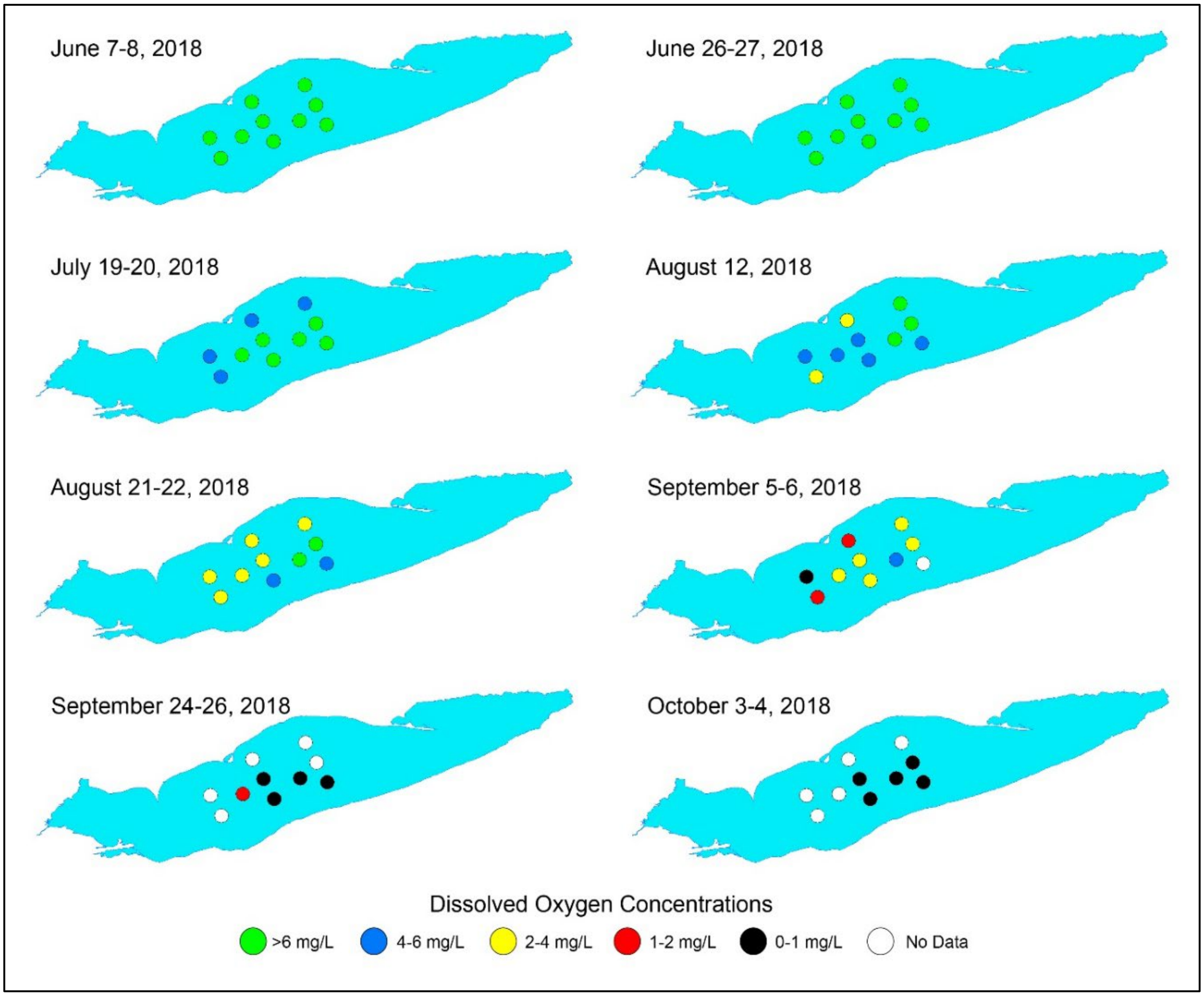

Figure 4. 2018 station means for hypolimnion DO concentrations in the central basin of Lake Erie.

Table 3. Mean water temperature (± SD) and DO for each survey in 2018.

2018 Survey dates	CTD used	Stations (#)	Epilimnion		Hypolimnion		
			Temperature (°C)	DO (mg/L)	Temperature (°C)	DO (mg/L)	Thickness (m)
June 7-8	SBE 911+	10	14.15 ± 0.50	9.27 ± 0.65	8.21 ± 0.68	9.70 ± 0.48	8.84 ± 1.64
June 26-27	SBE 911+	10	18.48 ± 0.45	9.26 ± 0.17	9.02 ± 1.27	8.43 ± 0.97	8.11 ± 2.59
July 19-20	SBE 911+	10	22.49 ± 0.32	9.02 ± 0.16	9.04 ± 0.59	6.62 ± 1.20	5.91 ± 1.60
August 12	SBE 911+	10	22.69 ± 1.76	8.24 ± 0.44	9.50 ± 0.36	5.33 ± 1.48	7.70 ± 2.06
August 21-22	SBE 19+	10	23.52 ± 1.81	7.94 ± 0.68	10.19 ± 0.79	4.32 ± 1.79	5.76 ± 1.24
September 5-6	SBE 911+	9	23.34 ± 0.62	8.40 ± 0.31	11.41 ± 1.20	2.37 ± 1.25	2.84 ± 2.85
September 24-26	SBE 19+	5	20.15 ± 0.43	7.88 ± 0.13	12.64 ± 1.28	0.39 ± 0.54	2.18 ± 1.36
October 3-4	SBE 911+	5	19.24 ± 0.45	8.30 ± 0.16	12.39 ± 0.93	0.12 ± 0.08	3.59 ± 0.66

2019 Synopsis

During the first survey (June 5, 2019), all stations were stratified with an average temperature difference of 4.5 °C between the epilimnion and hypolimnion layers (Table 4). Over the sampling season, average epilimnion temperatures increased from 12.3 °C to 23.5 °C (June to early August) and then began to decrease, reaching 20.8 °C by the end of the sampling period. The hypolimnion temperature increased from 7.8 °C to 14.5 °C. Average DO concentrations during the sampling season decreased from 11.4 mg O_2/L to 8.0 mg O_2/L in the epilimnion and from 9.8 mg O_2/L to 0.1 mg O_2/L in the hypolimnion.

Low DO concentrations (< 6 mg O_2/L) in the hypolimnion were first detected at the western and eastern-most sampling stations during the mid-July cruise. By the next survey (late July), the low oxygenated waters (< 6 mg O_2/L) had shifted westward; only the south eastern-most stations (ER31 and ER32) had DO concentrations > 6.0 mg O_2/L. Additionally, this was the first survey where DO concentrations < 4.0 mg O_2/L were observed (at ER42). While there were equipment issues (Table A.3) halfway through the August 26 survey, two of the sampled stations had hypolimnion DO concentrations < 2 mg O_2/L and one station (ER42) had a DO concentration < 1 mg O_2/L. By the beginning of September, half of the stations were hypoxic (< 2 mg O_2/L) and the other half were anoxic (< 1 mg O_2/L). Anoxic conditions were observed at all stations where data were available for the last two surveys of the season (Figure 5).

Winkler precision checks exceeded the acceptance criteria for approximately 18% of the samples collected (Appendix A). However, all Winkler-CTD accuracy checks for values above 5.0mg/L were within acceptance criteria.

An alternative method for assessing the quality of the CTD temperature measures was not able to be piloted in 2019. As a result, the QC temperature measurements were measured from the hull mounted transducer during this year. Use of a temperature sensor that can be attached directly to the CTD is planned to be piloted during the 2020 field season.

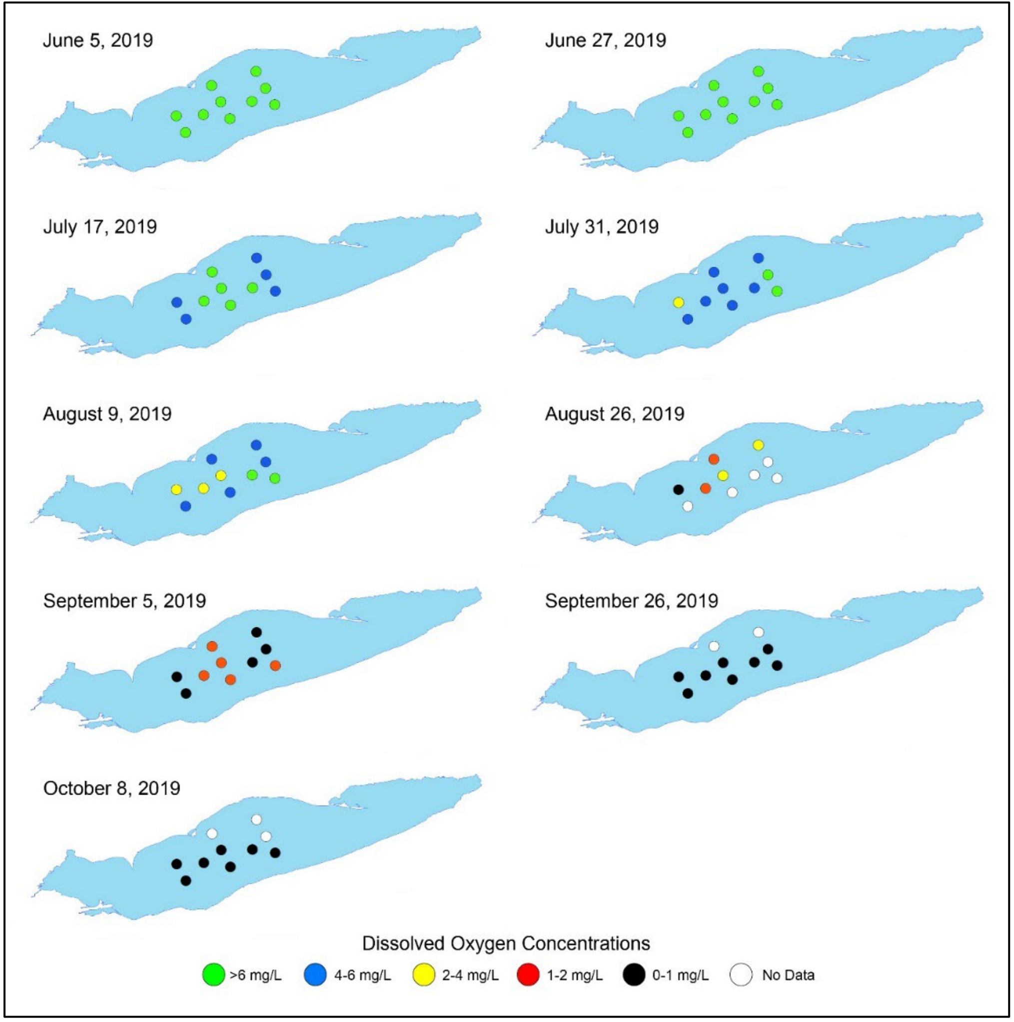

Figure 5. 2019 station means for hypolimnion DO concentrations in the central basin of Lake Erie.

Table 4. Mean water temperature (± SD) and DO for each survey in 2019.

2019 Survey dates	CTD used	Stations (#)	Epilimnion		Hypolimnion		
			Temperature (°C)	DO (mg/L)	Temperature (°C)	DO (mg/L)	Thickness (m)
June 5	SBE 911+	10	12.29 ± 0.64	11.35 ± 0.43	7.76 ± 0.61	9.8 ± 0.54	6.04 ± 1.49
June 27	SBE 911+	10	16.40 ± 0.47	10.23 ± 0.13	8.47 ± 0.60	8.15 ± 0.70	4.28 ± 1.57
July 17	SBE 911+	10	20.78 ± 0.61	8.90 ± 0.36	9.46 ± 0.99	5.70 ± 0.69	3.57 ± 1.90
July 31	SBE 19+	10	21.97 ± 3.51	8.07 ± 1.03	11.21 ± 1.36	5.24 ± 0.92	4.82 ± 2.27
August 9	SBE 911+	10	23.52 ± 1.81	7.94 ± 0.68	10.46 ± 0.99	4.59 ± 1.29	5.27 ± 1.99
August 26	SBE 19+	5	22.81 ± 1.17	8.17 ± 0.39	10.95 ± 0.81	1.90 ± 0.83	5.58 ± 1.20
September 5	SBE 911+	10	21.71 ± 1.26	7.76 ± 0.71	11.78 ± 0.87	0.83 ± 0.53	5.01 ± 2.49
September 26	SBE 19+	8	21.86 ± 0.21	8.53 ± 0.07	12.20 ± 0.84	0.10 ± 0.07	3.94 ± 1.51
October 8	SBE 19+	7	20.81 ± 0.20	7.99 ± 0.11	14.49 ± 2.96	0.10 ± 0.27	2.19 ± 2.01

Comparison to historical results

2017 Comparison

At the start of the 2017 season, the hypolimnion was significantly warmer than in 2011 and 2014-2016 (Table 5c), but still significantly cooler than in 2012 (Table 5c). The rate of change in hypolimnion temperature varied significantly between years (Table 5b), with the hypolimnion temperature increasing more slowly in 2017 than in 2013 and 2016 (Table 5b, 5c).

At the start of the 2017 season, the hypolimnion was significantly thicker than in 2009 and 2012, and thinner than in 2010 (Table 5c). The hypolimnion thickness approximated the previous 10-year average through most of the season. A slight increase in thickness occurred during the mid-September survey (approximately 0.5 m), but decreased to the second thinnest average hypolimnion by mid-October (Figure 7). The rate of change in hypolimnion thickness varied significantly between years (Table 5b), with the hypolimnion thickness decreasing more slowly in 2017 than in 2010, and faster than in years during which the thickness increased over time (i.e., 2009, 2011 and 2012) (Table 5c).

Throughout the 2017 season, the hypolimnion unadjusted DO concentration was significantly higher than throughout the 2012 season and significantly lower than in the 2008, 2014 and 2016 seasons. Furthermore, DO concentrations reached hypoxic conditions (< 2 mg O_2/L) by August 7, the second earliest date for this time period.

The corrected annual oxygen depletion rate for 2017 was 3.71 mg O_2/L/month (Figure 9). This is the second highest depletion rate since 2005. The last two surveys in 2017 (mid-September and early October) were not included in the oxygen depletion analysis. The average hypolimnion DO concentration during the mid-August survey was < 1.0 mg O_2/L with five stations ≤ 0.3 mg O_2/L. Additionally, two of the three stations which had oxygen levels > 1.0 mg O_2/L (ER30 and ER38) did not have a hypolimnion present during the mid-September survey, and therefore a depletion rate could not be calculated over that time period for those stations. Hypolimnion DO concentrations did not change between the mid-September and early October surveys. Of the four stations that had a hypolimnion present during both surveys, oxygen levels at two stations did not change between both surveys, while the oxygen concentration at the other two stations increased slightly over that time period (by 0.25 mg O_2/L and 0.01 mg O_2/L, respectively). As such, the inclusion of these surveys in the 2017 annual oxygen depletion rate calculation would artificially reduce the rate by dividing a static concentration (as no additional depletion occurred during this time period) by an additional 20 days (the time period of the last two survey.

2018 Comparison

At the start of the 2018 season (June 1), the hypolimnion was significantly warmer than in 2014, the coolest year over the 10-year period (Table 5f), but was still significantly cooler than the warmer years (2009, 2010, 2012, 2013 and 2017, Table 5f). The rate of change in hypolimnion temperature varied significantly between years (Table 5e), with the hypolimnion temperature increasing more slowly in 2018 than in 2013 and 2016 (Table 5f).

At the start of the 2018 season, the hypolimnion was significantly thicker than in 2009, 2011-2013 and 2017 (Table 5f). The rate of change in hypolimnion thickness varied significantly between years (Table 5e), with the hypolimnion thickness decreasing more slowly in 2018 than in years during which the thickness increased over time (i.e., 2009, 2011 and 2012) (Table 5f).

Throughout the 2018 season, the hypolimnion unadjusted DO was significantly higher than throughout the 2009 and 2012 seasons (Table 5f). Note that the rate of change in hypolimnion unadjusted DO did not vary significantly between years (Table 5e); however, since there is no significant interaction, a significant intercept (as indicated by a p-value less than alpha = 0.05 in Table 5f) can be interpreted as an overall difference between years.

The corrected annual oxygen depletion rate for 2018 was 2.88 mg O_2/L/month (Figure 9). This is the fourth lowest depletion rate since 2005 at approximately 0.32 mg O_2/L/month below the average for that time period.

2019 Comparison

Throughout the 2019 season, the hypolimnion temperature was significantly warmer than in 2014, the coolest year over the 10-year period (Table 5i), but still significantly cooler than in the warmer years (2010, 2012, 2013 and 2017, Table 5i). Note that the rate of change in hypolimnion temperature did not vary significantly between years (Table 5h); however, since there is no significant interaction, a significant intercept (as indicated by a p-value less than alpha = 0.05 in Table 5i) can be interpreted as an overall difference between years.

At the start of the 2019 season, the hypolimnion was significantly thicker than in 2012 and significantly thinner than in 2010, 2014, 2016 and 2018 (Table 5i). The rate of change in hypolimnion thickness varied significantly between years (Table 5h), with the hypolimnion thickness decreasing more slowly in 2019 than in 2010, 2016 and 2018 (Table 5i).

Throughout the 2019 season, the hypolimnion unadjusted DO was significantly higher than throughout the 2012 season and significantly lower than throughout the 2014 season (Table 5i). Note that the rate of change in hypolimnion unadjusted DO did not vary significantly between years (Table 5h); however, since there is no significant interaction, a significant intercept (as indicated by a p-value less than alpha = 0.05 in Table 5i) can be interpreted as an overall difference between years.

The corrected annual oxygen depletion rate for 2019 was 2.87 mg O_2/L/month (Figure 9). This was the third lowest depletion rate since 2005, at approximately 0.33 mg O_2/L/month below the average for that time period. The August 26 survey was not included in the 2019 depletion rate analysis because data were only recorded at half of the stations. A subsequent survey (September 5-6) was conducted approximately one week later in which all stations were able to be sampled which enabled depletion rates to be calculated at all stations during the August 9 – September 5 time interval. The final survey (October 8) was not included in the annual depletion rate calculation for 2019. All stations where hypolimnionic data were available, had reached anoxic conditions by the previous survey on September 26 (average DO concentration for the September 26 survey was 0.10 mg O_2/L). No further oxygen depletion occurred between the September 26 and October 8 surveys (average DO concentration for the October 8 survey was 0.10 mg O_2/L), and therefore this last survey was not included in the depletion rate calculation for this year.

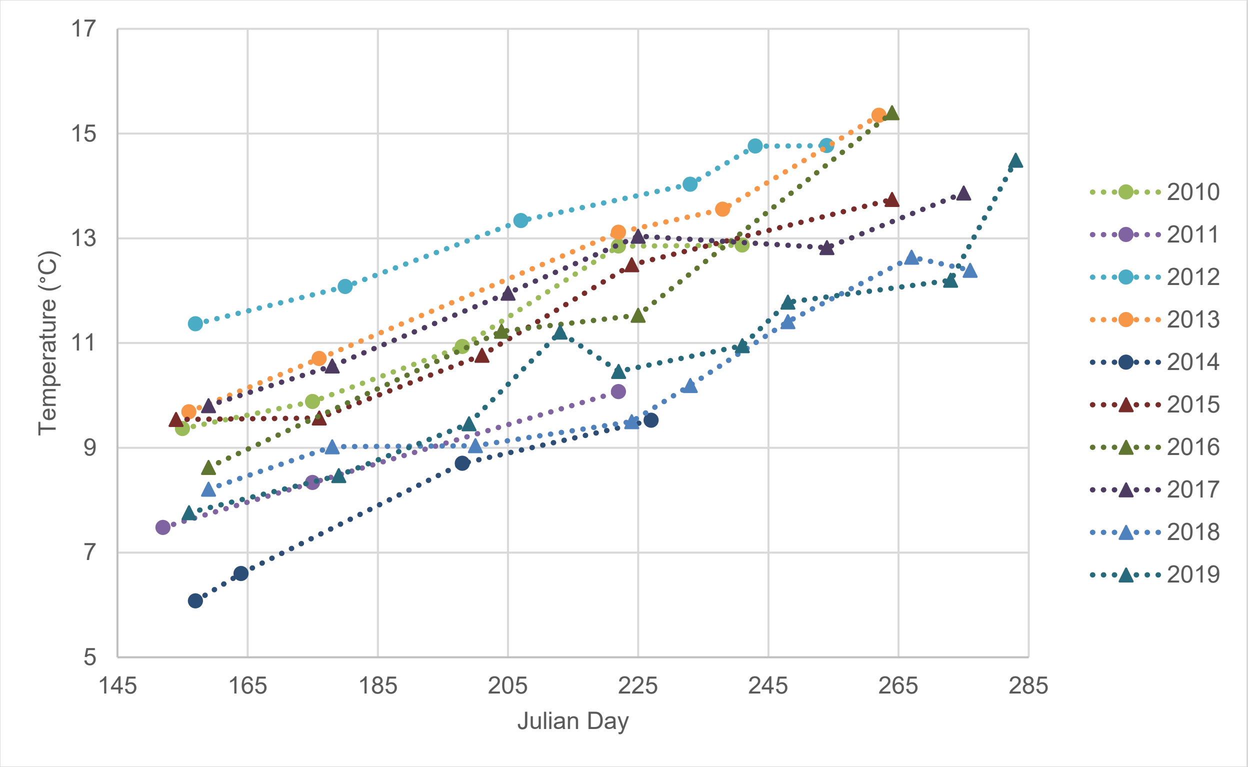

Figure 6. Survey mean hypolimnion temperatures in the central basin of Lake Erie from 2010-2019.

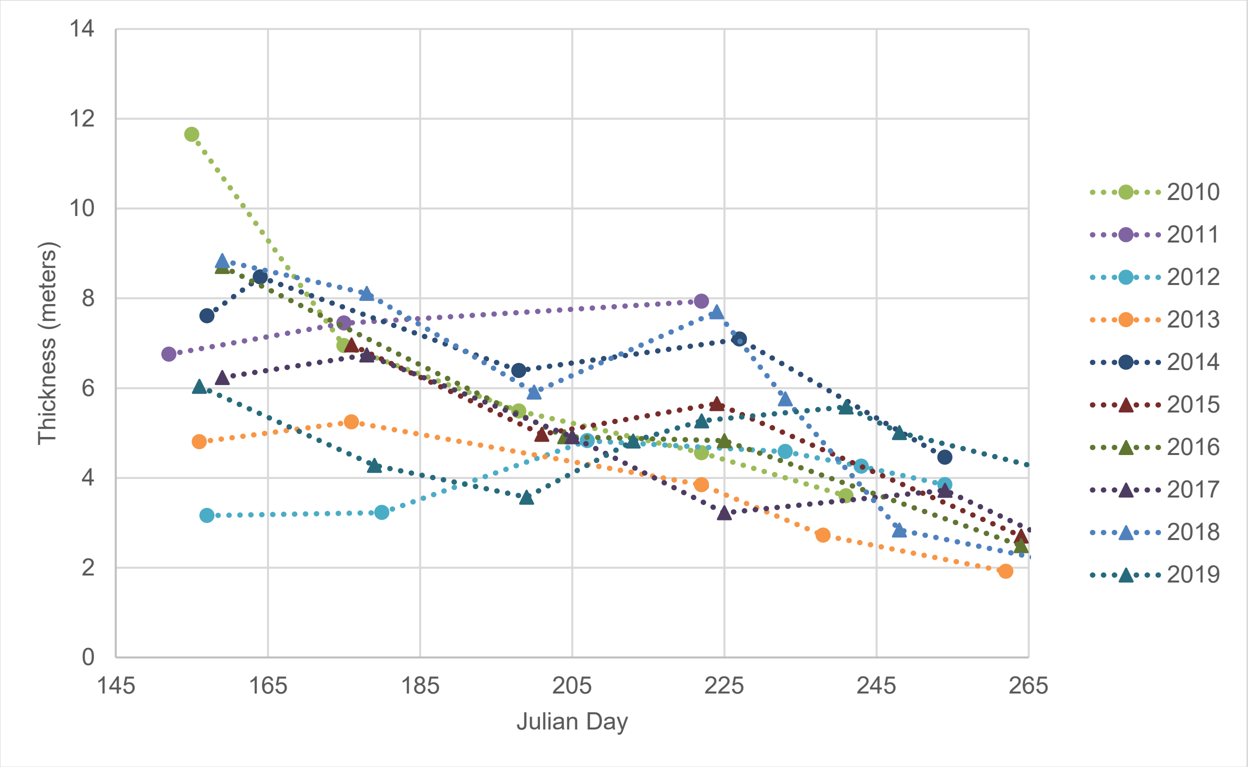

Figure 7. Survey mean hypolimnion thicknesses in the central basin of Lake Erie from 2010-2019.

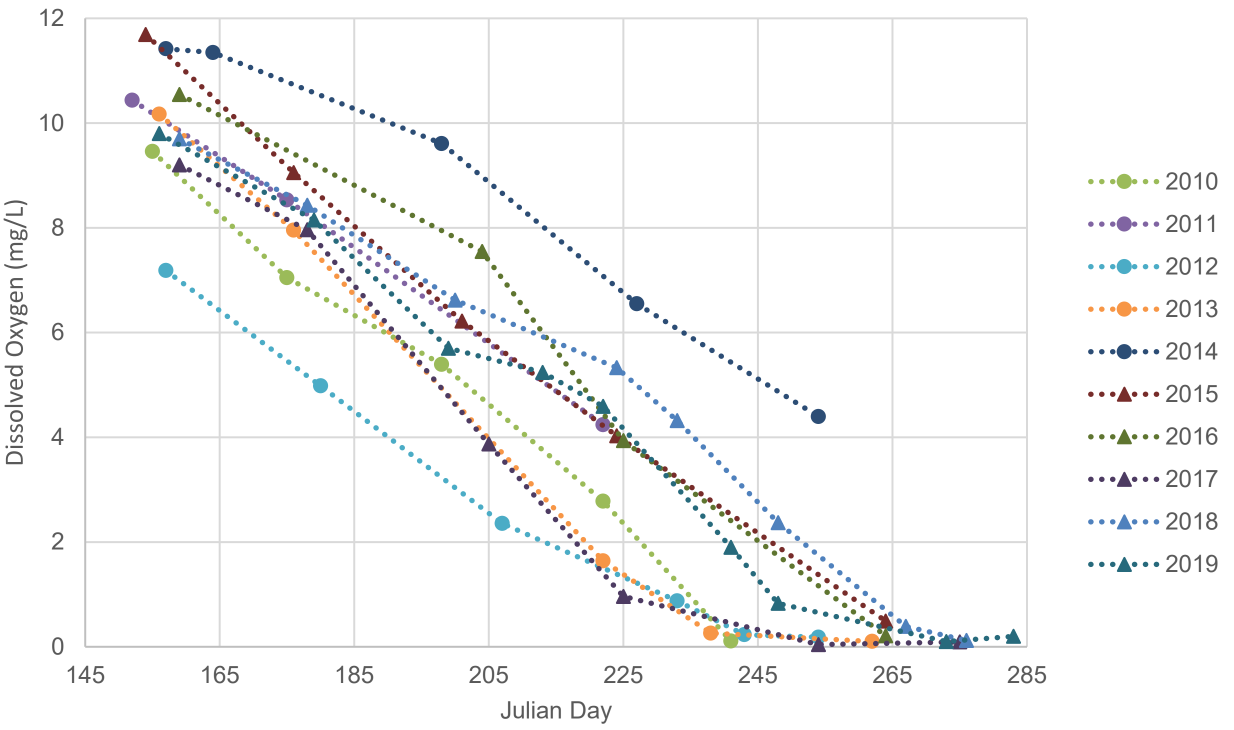

Figure 8. Survey mean hypolimnion dissolved oxygen concentrations in the central basin of Lake Erie from 2010-2019.

Table 5. Generalized linear model (GLM) results for the relationships between SurveyDay and hypolimnion temperature, thickness and DO concentration.

In the model, the SurveyDay term is defined as Julian day minus 150 to place the y-intercept near the beginning of the sampling period. The GLM model includes a separate factor for the sampling year, and a Julian day x year interaction term, which is used to test whether the rate of change in the hypolimnion temperature, thickness or DO varies significantly between years (i.e., whether the estimated slope varies between years). Statistical significance of the GLM model tests was set at alpha=0.05.

Table 5a. Overall GLM results for 2017.

Source	DF	Temperature					Thickness					DO concentration				
		Sum of Squares	Mean Square	F statistic[*]	p-value	R^2[†]	Sum of Squares	Mean Square	F statistic	p-value	R^2	Sum of Squares	Mean Square	F statistic	p-value	R^2
Model	19	225.65	11.88	70.06	<.0001	0.98	157.22	8.27	10.7	<.0001	0.88	667.61	35.14	67.77	<.0001	0.97
Error	29	4.92	0.17				22.44	0.77				15.04	0.52			

Table 5b. GLM fit statistics for 2017.

Source	DF	Temperature				Thickness				DO concentration			
		Type III SS[‡]	Mean Square	F statistic	p-value	Type III SS	Mean Square	F statistic	p-value	Type III SS	Mean Square	F statistic	p-value
SurveyDay[§]	1	101.20	101.20	596.95	<.0001	43.61	43.61	56.37	<.0001	463.72	463.72	655.52	<.0001
Year	9	27.06	3.01	17.74	<.0001	57.47	6.39	8.25	<.0001	33.22	3.69	5.22	0.0003
Interaction (i.e., SurveyDay x year)	9	5.35	0.59	3.51	0.0048	44.91	4.99	6.45	<.0001	9.16	1.02	1.44	0.2175

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[*] Ratio of the Mean Squares to its Error (i.e., overall model significance)

[†] Estimate of the overall variability explained by the model

[‡] Sum of Squares that includes the variation that is unique to the effect listed in that row (e.g., Temperature and SurveyDay) after adjusting for all other effects that are included in the model

[§] Julian day minus 150

Table 5c. GLM estimates of deviations in model intercept and slope used to calculate rate of change in water temperature, thickness and DO concentrations of the hypolimnion for years 2008-2016 compared to 2017 reference year.

Parameter	Temperature (˚C)				Thickness (m)				DO concentration (mg/L)			
	Estimate	Standard Error	T statistic[#]	p-value	Estimate	Standard Error	T statistic	p-value	Estimate	Standard Error	T statistic	p-value
Intercept in 2017	9.7863	0.3216	30.43	<.0001	6.9925	0.6871	10.18	<.0001	9.4262	0.6570	14.35	<.0001
Slope in 2017	0.0336	0.0042	8.1	<.0001	-0.0380	0.0089	-4.28	0.0002	-0.0870	0.0085	-10.25	<.0001
Difference in intercept in 2008††	-0.6860	0.4508	-1.52	0.1389	0.1997	0.9631	0.21	0.8372	2.0441	0.9209	2.22	0.0344
Difference in intercept in 2009	-0.2903	0.4524	-0.64	0.5262	-2.2916	0.9665	-2.37	0.0246	-0.8675	0.9242	-0.94	0.3557
Difference in intercept in 2010	-0.8190	0.4684	-1.75	0.0909	3.4977	1.0006	3.5	0.0015	0.5721	0.9568	0.6	0.5545
Difference in intercept in 2011	-2.3808	0.4821	-4.94	<.0001	-0.1398	1.0300	-0.14	0.893	1.2433	0.9849	1.26	0.2169
Difference in intercept in 2012	1.2988	0.4719	2.75	0.0101	-3.7021	1.0081	-3.67	0.001	-2.1560	0.9640	-2.24	0.0332
Difference in intercept in 2013	-0.4482	0.4677	-0.96	0.3458	-1.4719	0.9991	-1.47	0.1515	0.9421	0.9554	0.99	0.3322
Difference in intercept in 2014	-3.6884	0.4469	-8.25	<.0001	1.3765	0.9548	1.44	0.1601	2.9493	0.9130	3.23	0.0031
Difference in intercept in 2015	-1.3572	0.5686	-2.39	0.0237	0.9738	1.2147	0.8	0.4292	1.9154	1.1615	1.65	0.1099
Difference in intercept in 2016	-2.0056	0.5128	-3.91	0.0005	1.9394	1.0956	1.77	0.0872	2.4917	1.0476	2.38	0.0242
Difference in slope in 2008‡‡	-0.0034	0.0062	-0.54	0.5921	0.0157	0.0133	1.18	0.2495	-0.0170	0.0128	-1.33	0.1927
Difference in slope in 2009	0.0057	0.0065	0.89	0.3826	0.0391	0.0138	2.83	0.0084	0.0069	0.0132	0.52	0.6064
Difference in slope in 2010	0.0123	0.0072	1.69	0.1014	-0.0458	0.0155	-2.96	0.0061	-0.0176	0.0148	-1.19	0.2436
Difference in slope in 2011	0.0034	0.0092	0.37	0.7162	0.0539	0.0196	2.76	0.01	-0.0019	0.0187	-0.1	0.9185
Difference in slope in 2012	0.0033	0.0064	0.52	0.605	0.0492	0.0136	3.61	0.0011	0.0126	0.0130	0.97	0.3413
Difference in slope in 2013	0.0180	0.0063	2.88	0.0074	0.0081	0.0134	0.61	0.548	-0.0174	0.0128	-1.36	0.1855
Difference in slope in 2014	0.0082	0.0065	1.26	0.217	0.0067	0.0139	0.48	0.6321	0.0127	0.0133	0.96	0.3454
Difference in slope in 2015	0.0149	0.0076	1.96	0.0595	-0.0057	0.0162	-0.35	0.7296	-0.0095	0.0155	-0.61	0.5439
Difference in slope in 2016	0.0285	0.0068	4.17	0.0003	-0.0216	0.0146	-1.48	0.1498	-0.0140	0.0140	-1	0.326

[#] Ratio of the Estimate to its Standard Error

†† Factors are for the difference in the intercept from the reference (i.e., 2017) and the specific year. The tests (i.e., T statistic and p-value) determine if there is a significant difference between the intercept in the reference year (i.e., 2017) and the specific year. For example, in 2008, the estimated temperature intercept (i.e., estimated value on the 150th Julian day) is 9.1003 ˚C (9.7863 -0.6860), and it is not significantly different from the estimated temperature intercept in 2016 (i.e., 9.7863 ˚C) because the p-value is greater than alpha = 0.05.

‡‡ Factors are for the difference in the slope from the reference (i.e., 2017) and the specific year. The tests (i.e., T statistic and p-value) determine if there is a significant difference between the slope in the reference year (i.e., 2017) and the specific year. For example, in 2009, the estimated thickness slope is 0.0011 m/day (-0.0380 + 0.0391), and it is significantly different from the thickness slope in 2016S (i.e., -0.0380 m/day) because the p-value is less than alpha = 0.05.

Table 5d. Overall GLM results for 2018.

Source	DF	Temperature					Thickness					DO concentration				
		Sum of Squares	Mean Square	F statistic[*]	p-value	R^2[†]	Sum of Squares	Mean Square	F statistic	p-value	R^2	Sum of Squares	Mean Square	F statistic	p-value	R^2
Model	19	242.13	12.74	61.08	<.0001	0.97	186.62	9.82	10.48	<.0001	0.87	678.50	35.71	54.74	<.0001	0.97
Error	31	6.47	0.21				29.06	0.94				20.22	0.65			

Table 5e. GLM fit statistics for 2018.

Source	DF	Temperature				Thickness				DO concentration			
		Type III SS[‡]	Mean Square	F statistic	p-value	Type III SS	Mean Square	F statistic	p-value	Type III SS	Mean Square	F statistic	p-value
SurveyDay[§]	1	107.60	107.60	515.71	<.0001	55.28	55.28	58.98	<.0001	455.90	455.90	698.87	<.0001
Year	9	29.10	3.23	15.49	<.0001	68.07	7.56	8.07	<.0001	31.30	3.48	5.33	0.0002
Interaction (i.e., SurveyDay x year)	9	4.46	0.50	2.37	0.0356	50.64	5.63	6	<.0001	7.85	0.87	1.34	0.259

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[*] Ratio of the Mean Squares to its Error (i.e., overall model significance)

[†] Estimate of the overall variability explained by the model

[‡] Sum of Squares that includes the variation that is unique to the effect listed in that row (e.g., Temperature and SurveyDay) after adjusting for all other effects that are included in the model

[§] Julian day minus 150

Table 5f. GLM estimates of deviations in model intercept and slope used to calculate rate of change in water temperature, thickness and DO concentrations of the hypolimnion for years 2009-2017 compared to 2018 reference year.

Parameter	Temperature (˚C)				Thickness (m)				DO concentration (mg/L)			
	Estimate	Standard Error	T statistic[#]	p-value	Estimate	Standard Error	T statistic	p-value	Estimate	Standard Error	T statistic	p-value
Intercept in 2018	7.5253	0.3437	21.89	<.0001	9.5363	0.7285	13.09	<.0001	10.8485	0.6077	17.85	<.0001
Slope in 2018	0.0379	0.0041	9.15	<.0001	-0.0536	0.0088	-6.1	<.0001	-0.0846	0.0073	-11.54	<.0001
Difference in intercept in 2009	1.9708	0.4927	4	0.0004	-4.8353	1.0442	-4.63	<.0001	-2.2897	0.8711	-2.63	0.0132
Difference in intercept in 2010	1.4420	0.5107	2.82	0.0082	0.9539	1.0824	0.88	0.3849	-0.8501	0.9030	-0.94	0.3537
Difference in intercept in 2011††	-0.1197	0.5262	-0.23	0.8215	-2.6835	1.1153	-2.41	0.0223	-0.1789	0.9305	-0.19	0.8488
Difference in intercept in 2012	3.5598	0.5147	6.92	<.0001	-6.2458	1.0908	-5.73	<.0001	-3.5782	0.9100	-3.93	0.0004
Difference in intercept in 2013	1.8128	0.5099	3.56	0.0012	-4.0156	1.0808	-3.72	0.0008	-0.4801	0.9016	-0.53	0.5982
Difference in intercept in 2014	-1.4274	0.4865	-2.93	0.0062	-1.1672	1.0310	-1.13	0.2663	1.5271	0.8601	1.78	0.0856
Difference in intercept in 2015	0.9038	0.6235	1.45	0.1572	-1.5699	1.3214	-1.19	0.2438	0.4932	1.1024	0.45	0.6577
Difference in intercept in 2016	0.2554	0.5608	0.46	0.652	-0.6043	1.1886	-0.51	0.6148	1.0695	0.9916	1.08	0.2891
Difference in intercept in 2017	2.2610	0.4954	4.56	<.0001	-2.5437	1.0501	-2.42	0.0215	-1.4222	0.8760	-1.62	0.1146
Difference in slope in 2009‡‡	0.0014	0.0069	0.21	0.8359	0.0547	0.0146	3.74	0.0007	0.0046	0.0122	0.37	0.7112
Difference in slope in 2010	0.0080	0.0078	1.02	0.3145	-0.0303	0.0165	-1.83	0.0764	-0.0200	0.0138	-1.45	0.1573
Difference in slope in 2011	-0.0009	0.0100	-0.09	0.9253	0.0695	0.0211	3.29	0.0025	-0.0043	0.0176	-0.24	0.8102
Difference in slope in 2012	-0.0010	0.0068	-0.14	0.8876	0.0647	0.0144	4.5	<.0001	0.0103	0.0120	0.86	0.3986
Difference in slope in 2013	0.0137	0.0067	2.06	0.0476	0.0237	0.0141	1.68	0.1026	-0.0197	0.0118	-1.67	0.1043
Difference in slope in 2014	0.0039	0.0069	0.56	0.5776	0.0223	0.0147	1.52	0.1386	0.0104	0.0122	0.85	0.4023
Difference in slope in 2015	0.0106	0.0082	1.29	0.2049	0.0099	0.0173	0.57	0.5713	-0.0119	0.0145	-0.82	0.4186
Difference in slope in 2016	0.0242	0.0073	3.31	0.0024	-0.0060	0.0155	-0.39	0.7002	-0.0163	0.0129	-1.26	0.2173
Difference in slope in 2017	-0.0043	0.0062	-0.69	0.493	0.0156	0.0131	1.19	0.2446	-0.0023	0.0110	-0.21	0.8328

[#] Ratio of the Estimate to its Standard Error

†† Factors are for the difference in the intercept from the reference (i.e., 2018) and the specific year. The tests (i.e., T statistic and p-value) determine if there is a significant difference between the intercept in the reference year (i.e., 2018) and the specific year. For example, in 2011, the estimated temperature intercept (i.e., estimated value on the 150th Julian day) is 7.4056 ˚C (7.5253 -0.1197), and it is not significantly different from the estimated temperature intercept in 2018 (i.e., 7.5253 ˚C) because the p-value is greater than alpha = 0.05.

‡‡ Factors are for the difference in the slope from the reference (i.e., 2018) and the specific year. The tests (i.e., T statistic and p-value) determine if there is a significant difference between the slope in the reference year (i.e., 2018) and the specific year. For example, in 2009, the estimated thickness slope is 0.0011 m/day (-0.0536 + 0.0547), and it is significantly different from the thickness slope in 2018 (i.e., -0.0536 m/day) because the p-value is less than alpha = 0.05.

Table 5g. Overall GLM results for 2019.

Source	DF	Temperature					Thickness					DO concentration				
		Sum of Squares	Mean Square	F statistic[*]	p-value	R^2[†]	Sum of Squares	Mean Square	F statistic	p-value	R^2	Sum of Squares	Mean Square	F statistic	p-value	R^2
Model	19	262.17	13.80	53.87	<.0001	0.97	192.94	10.15	10.62	<.0001	0.85	735.32	38.70	61.57	<.0001	0.97
Error	35	8.97	0.26				33.46	0.96				22.00	0.63			

Table 5h. GLM fit statistics for 2019.

Source	DF	Temperature				Thickness				DO concentration			
		Type III SS[‡]	Mean Square	F statistic	p-value	Type III SS	Mean Square	F statistic	p-value	Type III SS	Mean Square	F statistic	p-value
SurveyDay[§]	1	115.93	115.93	452.59	<.0001	63.81	63.81	66.75	<.0001	478.73	478.73	761.59	<.0001
Year	9	29.66	3.30	12.87	<.0001	62.55	6.95	7.27	<.0001	26.31	2.92	4.65	0.0004
Interaction (i.e., SurveyDay x year)	9	4.51	0.50	1.95	0.0759	47.32	5.26	5.5	0.0001	7.86	0.87	1.39	0.2302

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[*] Ratio of the Mean Squares to its Error (i.e., overall model significance)

[†] Estimate of the overall variability explained by the model

[‡] Sum of Squares that includes the variation that is unique to the effect listed in that row (e.g., Temperature and SurveyDay) after adjusting for all other effects that are included in the model

[§] Julian day minus 150

Table 5i. GLM estimates of deviations in model intercept and slope used to calculate rate of change in water temperature, thickness and DO concentrations of the hypolimnion for years 2010-2018 compared to 2019 reference year.

Parameter	Temperature (˚C)				Thickness (m)				DO concentration (mg/L)			
	Estimate	Standard Error	T statistic[#]	p-value	Estimate	Standard Error	T statistic	p-value	Estimate	Standard Error	T statistic	p-value
Intercept in 2019	7.3469	0.3564	20.61	<.0001	5.6162	0.6886	8.16	<.0001	10.1378	0.5583	18.16	<.0001
Slope in 2019	0.0462	0.0043	10.85	<.0001	-0.0148	0.0082	-1.8	0.0798	-0.0824	0.0067	-12.36	<.0001
Difference in intercept in 2010††	1.6204	0.5497	2.95	0.0057	4.8740	1.0620	4.59	<.0001	-0.1395	0.8611	-0.16	0.8722
Difference in intercept in 2011	0.0586	0.5674	0.1	0.9183	1.2366	1.0962	1.13	0.267	0.5317	0.8889	0.6	0.5536
Difference in intercept in 2012	3.7382	0.5543	6.74	<.0001	-2.3257	1.0708	-2.17	0.0367	-2.8676	0.8683	-3.3	0.0022
Difference in intercept in 2013	1.9912	0.5488	3.63	0.0009	-0.0955	1.0603	-0.09	0.9287	0.2305	0.8598	0.27	0.7902
Difference in intercept in 2014	-1.2490	0.5220	-2.39	0.0222	2.7529	1.0085	2.73	0.0099	2.2377	0.8178	2.74	0.0097
Difference in intercept in 2015	1.0822	0.6777	1.6	0.1193	2.3502	1.3092	1.8	0.0813	1.2038	1.0616	1.13	0.2645
Difference in intercept in 2016	0.4338	0.6067	0.71	0.4794	3.3158	1.1722	2.83	0.0077	1.7801	0.9505	1.87	0.0695
Difference in intercept in 2017	2.4394	0.5323	4.58	<.0001	1.3764	1.0284	1.34	0.1894	-0.7116	0.8339	-0.85	0.3993
Difference in intercept in 2018	0.1784	0.5216	0.34	0.7344	3.9201	1.0077	3.89	0.0004	0.7106	0.8171	0.87	0.3904
Difference in slope in 2010‡‡	-0.0003	0.0085	-0.03	0.9753	-0.0690	0.0163	-4.23	0.0002	-0.0222	0.0132	-1.67	0.103
Difference in slope in 2011	-0.0092	0.0109	-0.84	0.4059	0.0307	0.0210	1.46	0.1535	-0.0065	0.0171	-0.38	0.7068
Difference in slope in 2012	-0.0092	0.0073	-1.26	0.2171	0.0260	0.0141	1.84	0.0745	0.0081	0.0115	0.7	0.4862
Difference in slope in 2013	0.0055	0.0072	0.77	0.4476	-0.0150	0.0138	-1.09	0.2846	-0.0219	0.0112	-1.95	0.0591
Difference in slope in 2014	-0.0043	0.0075	-0.58	0.566	-0.0165	0.0144	-1.14	0.2615	0.0082	0.0117	0.7	0.4887
Difference in slope in 2015	0.0024	0.0089	0.27	0.7914	-0.0288	0.0172	-1.68	0.1023	-0.0141	0.0139	-1.01	0.3198
Difference in slope in 2016	0.0160	0.0079	2.02	0.0516	-0.0448	0.0153	-2.93	0.006	-0.0185	0.0124	-1.49	0.1448
Difference in slope in 2017	-0.0125	0.0066	-1.88	0.0678	-0.0232	0.0128	-1.81	0.0796	-0.0045	0.0104	-0.44	0.6655
Difference in slope in 2018	-0.0082	0.0063	-1.31	0.1977	-0.0388	0.0121	-3.2	0.0029	-0.0022	0.0098	-0.22	0.8234

[#] Ratio of the Estimate to its Standard Error

†† Factors are for the difference in the intercept from the reference (i.e., 2019) and the specific year. The tests (i.e., T statistic and p-value) determine if there is a significant difference between the intercept in the reference year (i.e., 2019) and the specific year. For example, in 2011, the estimated temperature intercept (i.e., estimated value on the 150th Julian day) is 7.4056 ˚C (7.3469 +0.0586), and it is not significantly different from the estimated temperature intercept in 2019 (i.e., 7.3469 ˚C) because the p-value is greater than alpha = 0.05.

‡‡ Factors are for the difference in the slope from the reference (i.e., 2019) and the specific year. The tests (i.e., T statistic and p-value) determine if there is a significant difference between the slope in the reference year (i.e., 2019) and the specific year. For example, in 2010, the estimated thickness slope is -0.0839 m/day (-0.0148 -0.0690), and it is significantly different from the thickness slope in 2019 (i.e., -0.0148 m/day) because the p-value is less than alpha = 0.05.

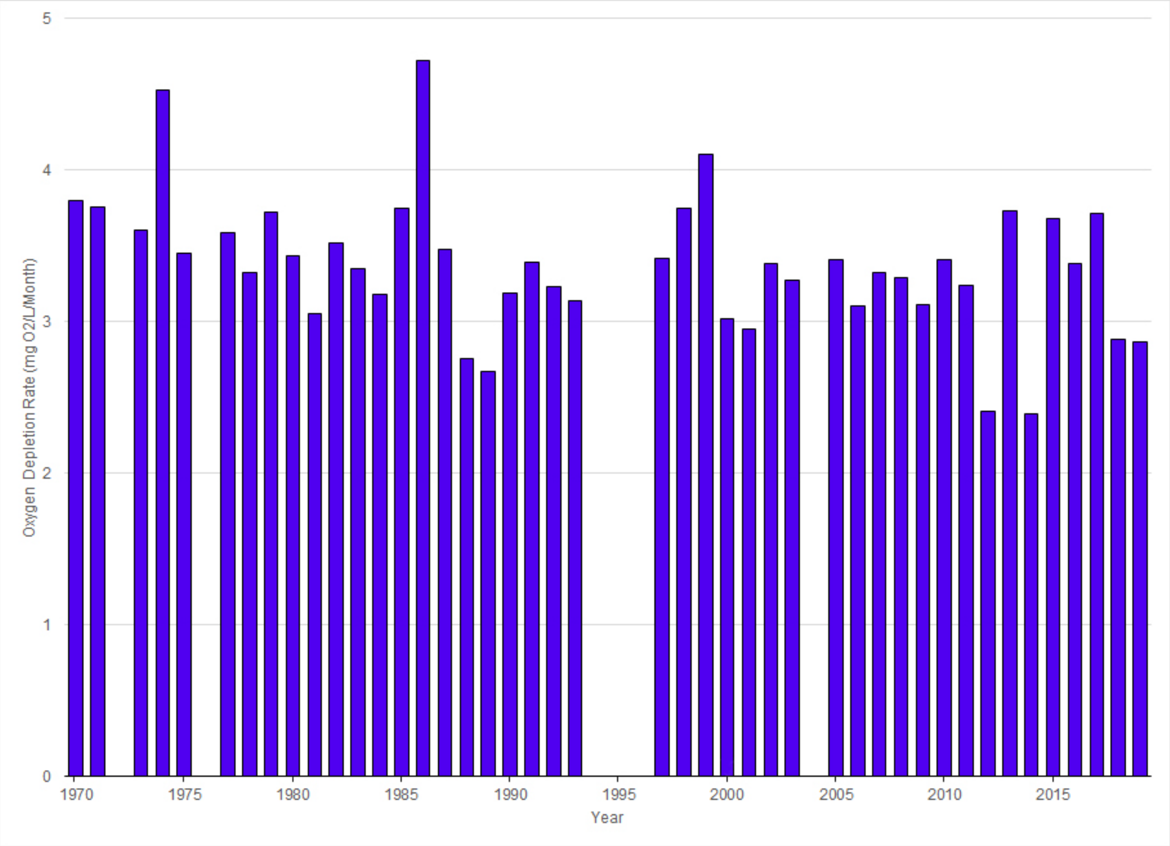

Figure 9. Annual dissolved oxygen depletion rate in the central basin of Lake Erie from 1970-2019.

6. CONCLUSIONS

U.S. EPA GLNPO Lake Erie Dissolved Oxygen Monitoring Program long-term observations reveal that over the course of the summer, DO levels in the bottom waters of Lake Erie's central basin steadily decline (Burns et al., 2005). Variability in the rate of DO depletion, its severity, and its duration are related to year-to-year differences in the thickness and temperature of the bottom water layer, as well as winter ice coverage. Year-to-year differences in the hypolimnion characteristics are determined by the weather over Lake Erie in the spring (i.e., average air temperature and wind velocity). Rapidly climbing air temperature with calm winds will result in a thinner, warmer epilimnion and a thicker, cooler hypolimnion that retains more DO longer into the season. A cooler, windy spring will permit the entire water column to warm before the lake stratifies, resulting in a deeper thermocline depth and a warm, thin hypolimnion that is more prone to oxygen depletion earlier in the season (Conroy et al., 2011; Bocaniov, 2020). Furthermore, reduced ice coverage over the winter can result in earlier springtime mixing and a longer stratification period, thus increasing the risk of oxygen depletion in the hypolimnion (Perello, 2017).

In 2017-2019, hypoxic and anoxic conditions were observed in all three sampling seasons by our ship-based observations. However, seasonal variations led to annual differences in the onset, extent, and duration of these low-oxygen conditions during each year. 2017 exhibited one of the higher annual dissolved oxygen depletion rates observed in the last two decades, which led to the presence of anoxic conditions much earlier in the season than had been recorded in recent preceding years. On the other hand, 2018 and 2019 exhibited two of the lowest annual dissolved oxygen depletion rates, and anoxia was not seen until almost a month later during these seasons compared to 2017.

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APPENDIX A - QUALITY CONTROL RESULTS

A summary of 2017 results not meeting acceptance criteria is provided in the table below.

Table A-1. Quality control (QC) scorecard of 2017 CTD-collected temperature and dissolved oxygen (DO) data not meeting acceptance criteria.

Survey	Issue	Cause	Decision	Corrective Actions
June 8	Temperature accuracy check exceeded QC criterion (1 of 2 samples)	Temperature of the hull may be affecting the measurements from the hull-mounted transducer.	Suspected issue with QC sample methodology and does not affect quality of CTD data. CTD temperature values are considered valid.	Independent temperature sensor will be used for 2018 surveys.
	Winkler precision check exceeded the QC criterion (1 of 4 samples)	Analyst error	QC sample exceedance does not affect quality of CTD data. CTD DO values are considered valid.	Additional training and/or observational period will be required for inexperienced analysts. Run additional replicate analyses until consistency is achieved.
June 27	Temperature accuracy check exceeded QC criterion (5 of 10 samples)	Temperature of the hull may be affecting the measurements from the hull-mounted transducer.	Suspected issue with QC sample methodology and does not affect quality of CTD data. CTD temperature values are considered valid.	Independent temperature sensor will be used for 2018 surveys.
	Winkler precision check exceeded the QC criterion (6 of 17 samples)	Analyst error	QC sample exceedance does not affect quality of CTD data. CTD DO values are considered valid.	Additional training and/or observational period will be required for inexperienced analysts. Run additional replicate analyses until consistency is achieved.
July 24-25	Temperature accuracy check exceeded QC criterion (2 of 10 samples)	Temperature of the hull may be affecting the measurements from the hull-mounted transducer.	Suspected issue with QC sample methodology and does not affect quality of CTD data. CTD temperature values are considered valid.	Independent temperature sensor will be used for 2018 surveys.

Survey	Issue	Cause	Decision	Corrective Actions
	Winkler precision check exceeded the QC criterion (5 of 14 samples)	Analyst error	QC sample exceedance does not affect quality of CTD data. CTD DO values are considered valid.	Additional training and/or observational period will be required for inexperienced analysts. Run additional replicate analyses until consistency is achieved.
	SeaBird vs. Winkler for <5.00 mg/L Accuracy differences exceeded the QC criterion (2 of 6 samples)	Due to a thin hypolimnion, thermocline or epilimnion water may have been present in the Winkler samples.	All samples where DO >5.00mg/L were within QC criteria (9 of 9 samples). CTD DO values are considered valid.	Not Applicable
Aug 13-14	Winkler precision check exceeded the QC criterion (2 of 4 samples)	Analyst error	QC sample exceedance does not affect quality of CTD data. CTD DO values are considered valid.	Additional training and/or observational period will be required for inexperienced analysts. Run additional replicate analyses until consistency is achieved.
	SeaBird vs. Winkler for <5.00 mg/L Accuracy differences exceeded the QC criterion (2 of 2 samples)	Due to a thin hypolimnion, thermocline or epilimnion water may have been present in the Winkler sample.	The accuracy RPD for both surface samples passed the QC criterion. CTD DO values are considered valid.	Not Applicable
Sept 11-12	Temperature accuracy check exceeded QC criterion (4 of 10 samples)	Temperature of the hull may be affecting the measurements from the hull-mounted transducer.	Suspected issue with QC sample methodology and does not affect quality of CTD data. CTD temperature values are considered valid.	Independent temperature sensor will be used for 2018 surveys.
	Winkler precision check exceeded the QC criterion (4 of 15 samples)	Analyst error	QC sample exceedance does not affect quality of CTD data. CTD DO values are considered valid.	Additional training and/or observational period will be required for inexperienced analysts. Run additional replicate analyses until consistency is achieved.
	CTD DO accuracy check exceeded the QC criterion (1 of 8)	Undetermined. Probe values were slightly higher than neighboring stations.	CTD DO values for ER31 are not considered valid.	Recast CTD and/or re-sample for Winkler Titration while on station, if possible.

Survey	Issue	Cause	Decision	Corrective Actions
	SeaBird vs. Winkler for <5.00 mg/L Accuracy differences exceeded the QC criterion (5 of 7 samples)	Due to a thin hypolimnion, thermocline or epilimnion water may have been present in the Winkler sample.	8 of 9 samples where DO >5.00 mg/L were within QC criteria. CTD DO values are considered valid.	Not Applicable
Oct 2-3	Winkler precision check exceeded the QC criterion (4 of 12 samples)	Analyst error	QC sample exceedance does not affect quality of CTD data. CTD DO values are considered valid.	Additional training and/or observational period will be required for inexperienced analysts. Run additional replicate analyses until consistency is achieved.

A summary of 2018 results not meeting acceptance criteria is provided in the table below.

Table A-2. Quality control (QC) scorecard of 2018 CTD-collected temperature and dissolved oxygen (DO) data not meeting acceptance criteria.

Survey	Issue	Cause	Decision	Corrective Actions
June 7-8	Temperature accuracy check exceeded QC criterion (1 of 2 samples)	Surface Temp and Probe Temp may not have been taken at same depth.	Suspected issue with QC sample methodology and does not affect quality of CTD data. CTD temperature values are considered valid.	Ensure routine and QC measurements are taken at the same depth.
June 26-27	Winkler precision check exceeded the QC criterion (3 of 4 samples)	Analyst error.	Replicate CTD casts are within QC criteria. CTD DO values are considered valid.	Run additional replicate analyses until consistency is achieved.
July 19-20	Winkler precision check exceeded the QC criterion (1 of 4 samples)	Titrant ran out on station. Titrant may have been too concentrated.	QC sample exceedance does not affect quality of CTD data. CTD DO values are considered valid.	Ensure there is enough titrant for entire station before beginning analysis.
Aug 13-14	Winkler precision check exceeded the QC criterion (2 of 4 samples)	Cause cannot be determined.	QC sample exceedance does not affect quality of CTD data. CTD DO values are considered valid.	Run additional replicate analyses until consistency is achieved.
Aug 21-22	Winkler precision check exceeded the QC criterion (2 of 4 samples)	Cause cannot be determined.	QC sample exceedance does not affect quality of CTD data. CTD DO values are considered valid.	Run additional replicate analyses until consistency is achieved.
Sept 5-6	SeaBird vs. Winkler for <5.00 mg/L Accuracy differences exceeded the QC criterion (1 of 2 samples)	Oxygen may have been introduced to sample via bubbles. CTD DO value is 0.06 mg/L.	Surface sample for this station (DO >5.00 mg/L) met QC criterion. CTD DO values are considered valid.	Care should be used when filling collection bottle to reduce the risk of introducing air bubbles to the sample. Run additional replicate analyses until consistency is achieved.

Survey	Issue	Cause	Decision	Corrective Actions
Sept 24-26	Winkler precision check exceeded the QC criterion (1 of 4 samples)	Cause cannot be determined.	QC sample exceedance does not affect quality of CTD data. CTD DO values are considered valid.	Run additional replicate analyses until consistency is achieved.
	Temperature accuracy check exceeded QC criterion (2 of 2 samples)	Surface Temp and Probe Temp may not have been taken at same depth.	Suspected issue with QC sample methodology and does not affect quality of CTD data. CTD temperature values are considered valid.	Ensure routine and QC measurements are taken at the same depth.
Oct 3-4	Temperature accuracy check exceeded QC criterion (1 of 2 samples)	Surface Temp and Probe Temp may not have been taken at same depth.	Suspected issue with QC sample methodology and does not affect quality of CTD data. CTD temperature values are considered valid.	Ensure routine and QC measurements are taken at the same depth.

A summary of 2019 results not meeting acceptance criteria is provided in the table below.

Table A-3. Quality control (QC) scorecard of 2019 CTD-collected temperature and dissolved oxygen (DO) data not meeting acceptance criteria.

Survey	Issue	Cause	Decision	Corrective Actions
June 5	Winkler precision check exceeded the QC criterion (1 of 5 samples)	Cause cannot be determined. Sample was 0.02 mg/L above limit.	QC sample exceedance does not affect quality of CTD data. CTD DO values are considered valid.	Run additional replicate analyses until consistency is achieved.
	Temperature accuracy check exceeded QC criterion (1 of 3 samples)	Surface Temp and Probe Temp may not have been taken at same depth.	Suspected issue with QC sample methodology and does not affect quality of CTD data. CTD temperature values are considered valid.	Ensure routine and QC measurements are taken at the same depth.
June 27	Winkler precision check exceeded the QC criterion (1 of 4 samples)	Cause cannot be determined. Sample was 0.02 mg/L above limit.	QC sample exceedance does not affect quality of CTD data. CTD DO values are considered valid.	Run additional replicate analyses until consistency is achieved.
July 17	Winkler precision check exceeded the QC criterion (1 of 4 samples)	Oxygen may have been introduced to sample via bubbles.	QC sample exceedance does not affect quality of CTD data. CTD DO values are considered valid.	Run additional replicate analyses until consistency is achieved.
	Temperature accuracy check exceeded QC criterion (2 of 2 samples)	Surface temperatures were not taken during survey. Surface temperature values nearest NOAA surface buoy were used.	CTD Temperature values cannot be varied. Descension should be used for this dataset.	Ensure surface temperature measurements are made during the survey.
July 31	Winkler precision check exceeded the QC criterion (1 of 4 samples)	Cause cannot be determined. Sample was 0.01 mg/L above limit.	QC sample exceedance does not affect quality of CTD data. CTD DO values are considered valid.	Run additional replicate analyses until consistency is achieved.
	Temperature accuracy check exceeded QC criterion (2 of 2 samples)	Surface Temp and Probe Temp may not have been taken at same depth.	CTD Temperature values cannot be varied. Descension should be used for this dataset.	Ensure routine and QC measurements are taken at the same depth.
Aug 26	Temperature accuracy check exceeded QC criterion (1 of 1 samples)	Surface Temp and Probe Temp may not have been taken at same depth.	CTD Temperature values cannot be varied. Descension should be used for this dataset.	Ensure routine and QC measurements are taken at the same depth.

Survey	Issue	Cause	Decision	Corrective Actions
Sept 5	Winkler precision check exceeded the QC criterion (1 of 4 samples)	One sample was much lower (0.61 mg/L) than the others. Titration might not have been completed to appropriate end point.	QC sample exceedance does not affect quality of CTD data. CTD DO values are considered valid.	Run additional replicate analyses until consistency is achieved.
Sept 26	Winkler precision check exceeded the QC criterion (2 of 4 samples)	Cause cannot be determined.	QC sample exceedance does not affect quality of CTD data. CTD DO values are considered valid.	Run additional replicate analyses until consistency is achieved.
	Temperature accuracy check exceeded QC criterion (2 of 2 samples)	Surface Temp and Probe Temp may not have been taken at same depth.	CTD Temperature values cannot be varied. Descension should be used for this dataset.	Ensure routine and QC measurements are taken at the same depth.
Oct 9	Winkler precision check exceeded the QC criterion (1 of 4 samples)	Oxygen may have been introduced to sample via bubbles. CTD DO value is 0.25 mg/L.	QC sample exceedance does not affect quality of CTD data. CTD DO values are considered valid.	Care should be used when filling collection bottle to reduce the risk of introducing air bubbles to the sample. Run additional replicate analyses until consistency is achieved.
	Temperature accuracy check exceeded QC criterion (2 of 2 samples)	Surface Temp and Probe Temp may not have been taken at same depth.	CTD Temperature values cannot be varied. Descension should be used for this dataset.	Ensure routine and QC measurements are taken at the same depth.