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 2021

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Great Lakes
RESTORATION

Prepared By:
United States Environmental Protection Agency
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Cover photo: Sunrise from coast of Kelleys Island in Lake Erie by Becky Swora.

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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 annually 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.

During the course of the 2021 sampling season (June 14 – October 7):

- Seven surveys were conducted during the 2021 field season using the USGS R/V *Muskie.*
- Surface water temperatures increased from 17.5 °C to 23.1 °C, while hypolimnion temperatures increased from 10.91 °C to 15.2 °C.
- Hypolimnion DO concentrations during the sampling season decreased from approximately 9.0 mg O_2/L to 0.36 mg O_2/L.
- Low-oxygen conditions (< 6 mg O_2/L) were first recorded on July 28, 2021 (all stations).
- Anoxic conditions (< 1 mg O_2/L) were first recorded during the August 24-25, 2021 survey (all stations).
- The annual corrected oxygen depletion rate was 4.32 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 in size compared to observations from 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, 2018a), 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, 2018a). 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 2021 Lake Erie Dissolved Oxygen Monitoring Program surveys and places those results within the context of historical data, where possible.

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 all seven surveys during 2021.

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 2021, a SeaBird Scientific SBE 19plus V2 SeaCAT Profiler CTD was used for collecting water temperature data, and a SBE43 Dissolved Oxygen Sensor was used for collecting DO data. 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, 2018b).

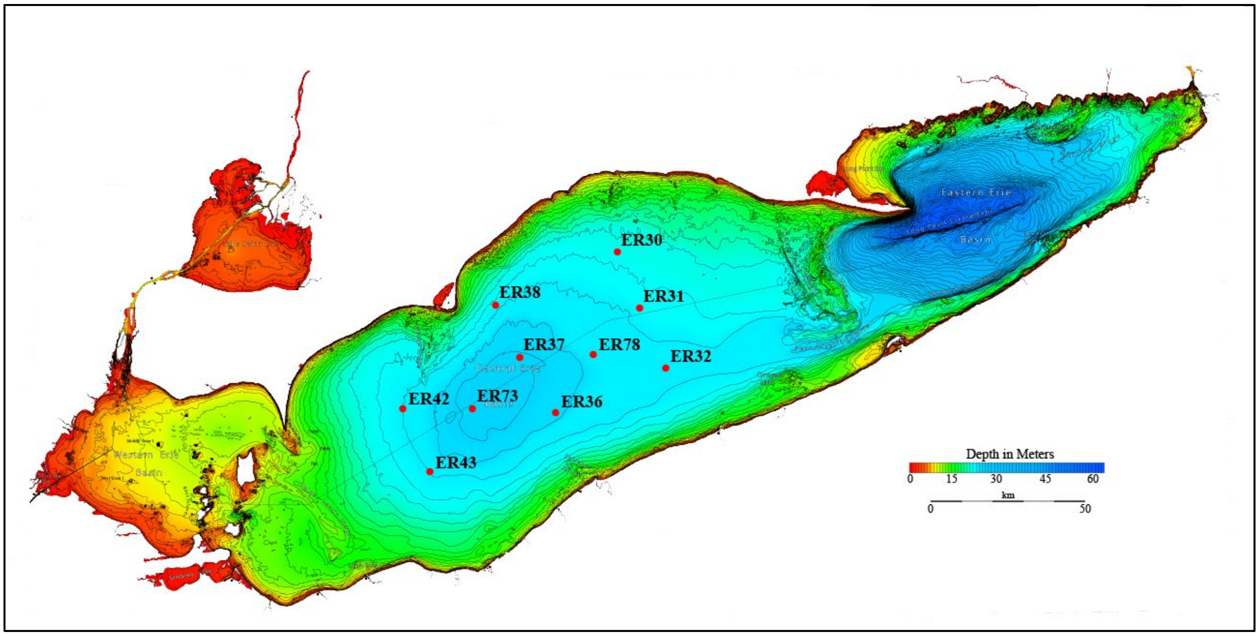

Figure 1. Map of GLNPO DO monitoring stations in the central basin of Lake Erie.

Quality Assurance samples were 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, 2018b) 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.

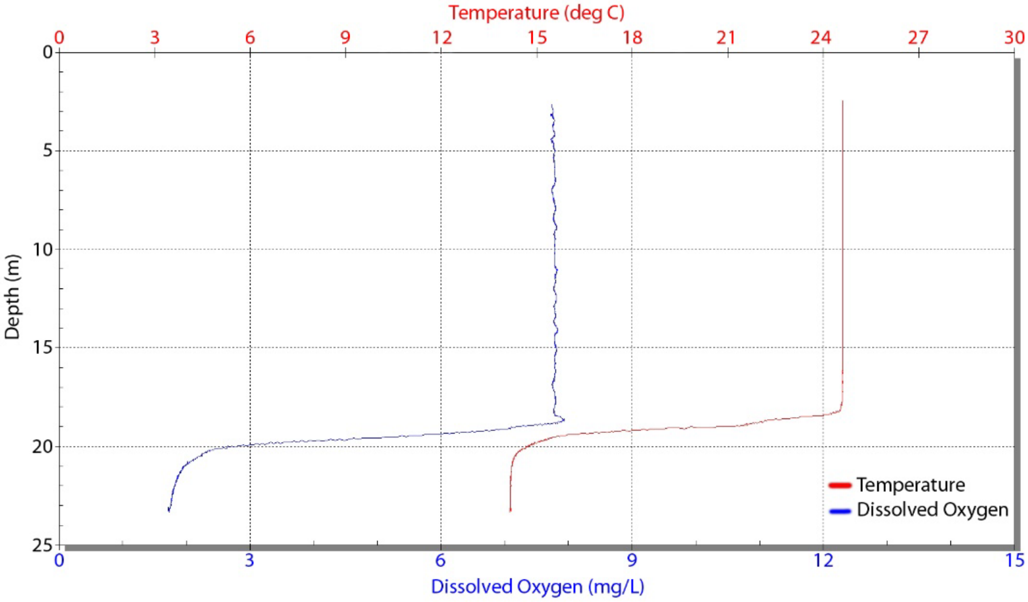

Figure 2. Example of a temperature and DO depth profile from Lake Erie central basin in late summer.

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 (2012-2021) 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 3) and either hypolimnion temperature, thickness or DO concentration (Tables 3a, 3b and 3c). 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 2021 surveys operated under Revision 11 of the QAPP (U.S. EPA, 2018b). 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 criterion 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

During the first survey (June 14-15, 2021), all stations were stratified with an average temperature difference of 6.5 °C between the epilimnion and hypolimnion layers (Table 2). Over the sampling season, average temperatures increased in the epilimnion from 17.5 °C to 23.8 °C and in the hypolimnion from 10.9 °C to 15.2 °C. Average DO concentrations during the sampling season decreased from 10.0 mg O_2/L to 7.8 mg O_2/L in the epilimnion and from 9.0 mg O_2/L to 0.36 mg O_2/L in the hypolimnion.

Low DO concentrations (< 6 mg O_2/L) in the hypolimnion were detected at all 10 stations during the July 27-28 cruise. By late August, all stations had become anoxic (< 1 mg O_2/L). During September and early October all stations that had a hypolimnion present continued to experience anoxic conditions (Figure 3).

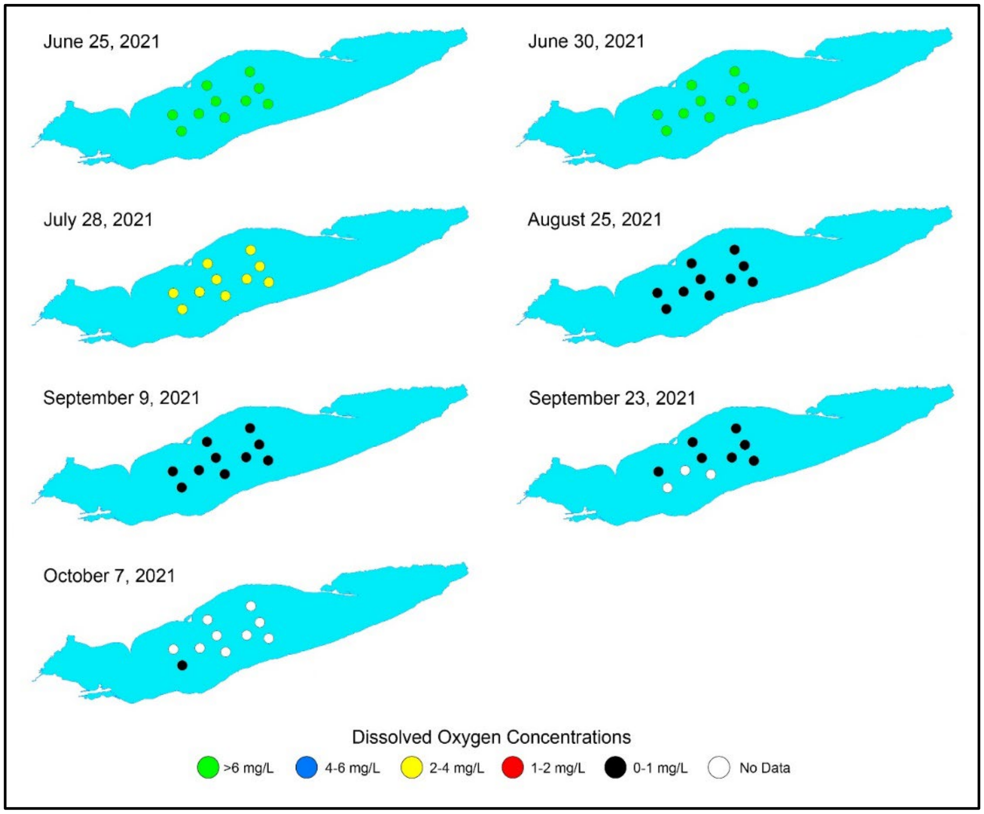

Figure 3. 2021 station means for hypolimnion DO concentrations in the central basin of Lake Erie.

Table 2. Mean water temperature (± SD) and DO for each survey in 2021.

2021 Survey dates	CTD used	Stations (#)	Epilimnion		Hypolimnion		
			Temperature (°C)	DO (mg/L)	Temperature (°C)	DO (mg/L)	Thickness (m)
June 14-15	SBE 19+	10	17.45 ± 0.78	10.05 ± 0.27	10.91 ± 0.51	9.00 ± 0.39	11.33 ± 1.80
June 29-30	SBE 19+	10	19.07 ± 0.48	9.51 ± 0.43	11.09 ± 0.53	7.31 ± 0.45	5.79 ± 2.34
July 27-28	SBE 19+	10	22.00 ± 0.51	8.99 ± 0.23	11.44 ± 0.29	3.17 ± 0.52	6.42 ± 0.64
August 24-25	SBE 19+	10	23.81 ± 0.37	8.03 ± 0.17	11.81 ± 0.18	0.43 ± 0.25	5.54 ± 1.98
September 8-9	SBE 19+	10	22.71 ± 0.49	7.78 ± 0.10	12.51 ± 0.32	0.36 ± 0.10	4.46 ± 1.40
September 20-21	SBE 19+	7	21.49 ± 1.34	7.96 ± 0.33	13.31 ± 0.54	0.38 ± 0.21	3.76 ± 2.89
October 6-7	SBE 19+	1	19.38	8.48	15.22	0.88	3.52

6. COMPARISON TO HISTORICAL RESULTS

Throughout the 2021 season, the hypolimnion temperature was significantly warmer than in 2014, 2016, 2018, and 2019 (Table 3c). These were the coolest years over the 10-year period (Figure 4). Note that the rate of change in hypolimnion temperature did not vary significantly between years (Table 3b); however, since there is no significant interaction, a significant intercept (as indicated by a p-value less than alpha = 0.05 in Table 3c) can be interpreted as an overall difference between years.

Throughout the 2021 season, the hypolimnion was significantly thicker than in 2012, 2013, and 2019 (Table 3c). These were the years with the thinnest hypolimnion over the 10-year period (Figure 5). Note that the rate of change in hypolimnion thickness did not vary significantly between years (Table 3b); however, since there is no significant interaction, a significant intercept (as indicated by a p-value less than alpha = 0.05 in Table 3c) can be interpreted as an overall difference between years.

Throughout the 2021 season, the hypolimnion unadjusted DO was significantly lower than throughout the 2014 season (Figure 6, Table 3c). Note that the rate of change in hypolimnion unadjusted DO did not vary significantly between years (Table 3b); however, since there is no significant interaction, a significant intercept (as indicated by a p-value less than alpha = 0.05 in Table 3c) can be interpreted as an overall difference between years.

The corrected annual oxygen depletion rate for 2021 was 4.32 mg O_2/L/month (Figure 7). This is the third highest recorded depletion rate since 1970 and the highest seen since 1986. The last three surveys in 2021 (early September through early October) were not included in the oxygen depletion analysis because the average hypolimnion DO concentration during the August 24-25 had already reached anoxic conditions (0.43 mg/L) and thus additional survey data are not warranted for this calculation.

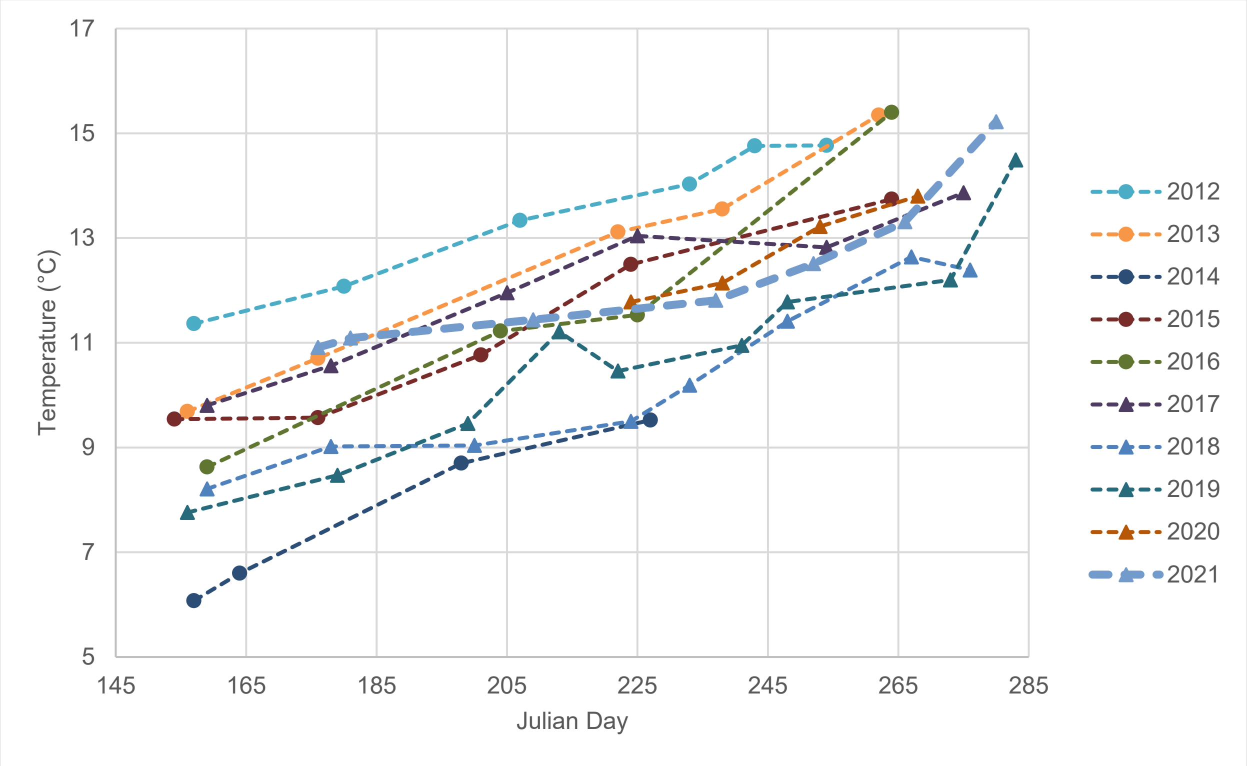

Figure 4. Survey mean hypolimnion temperatures in the central basin of Lake Erie from 2012-2021.

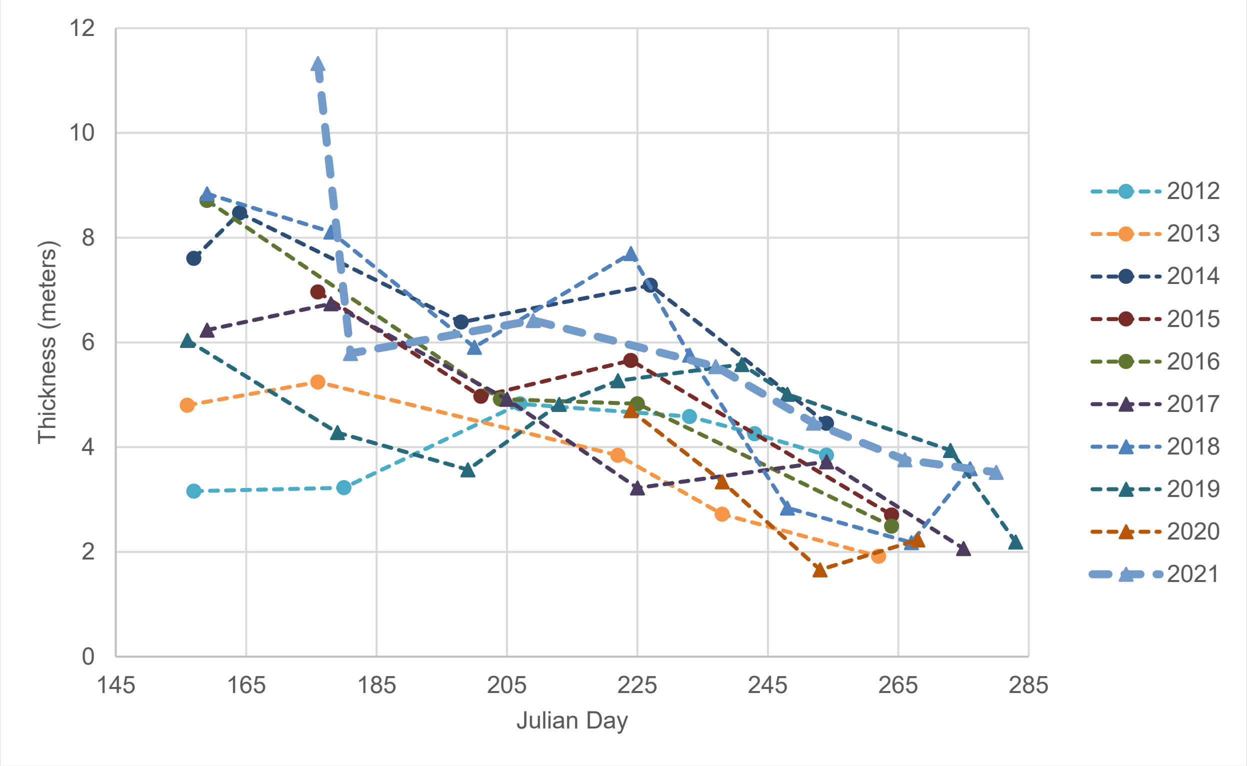

Figure 5. Survey mean hypolimnion thicknesses in the central basin of Lake Erie from 2012-2021.

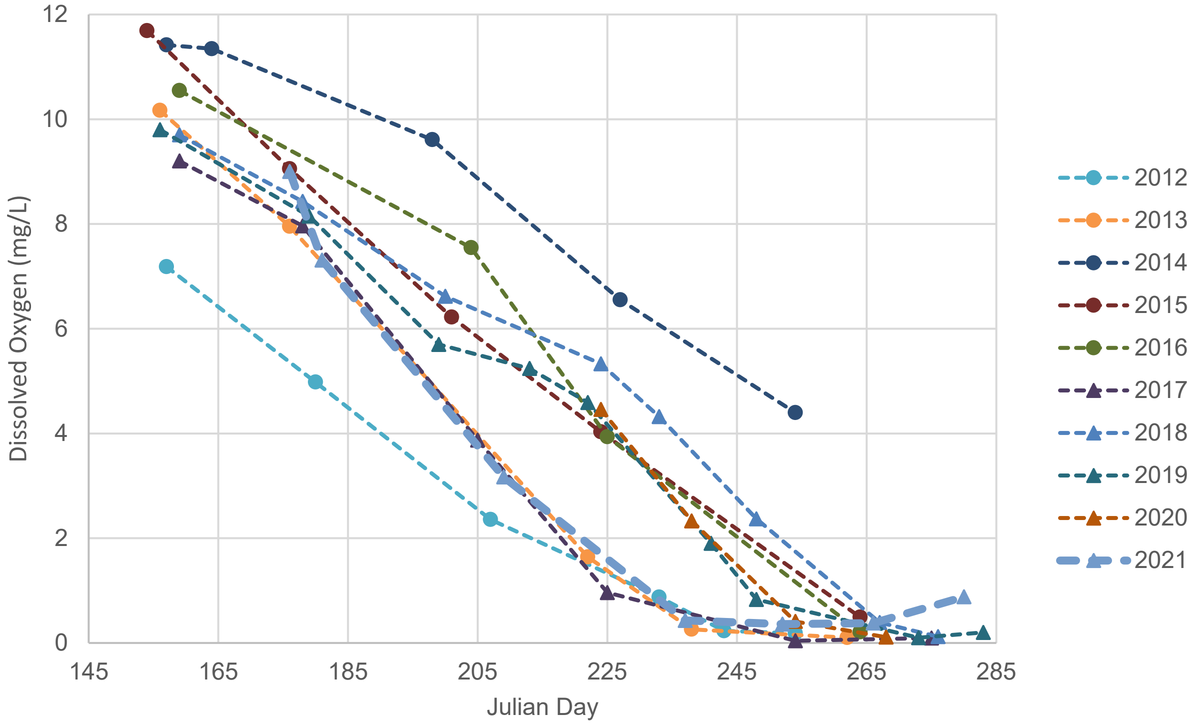

Figure 6. Survey mean hypolimnion DO concentrations in the central basin of Lake Erie from 2012-2021.

Table 3. 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 3a. Overall GLM results for 2021.

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	17	177.4260968	10.4368292	29.74	<.0001	0.945754	124.6945743	7.334975	5.46	<.0001	0.762020	482.6298383	28.3899905	25.65	<.0001	0.93763
Error	29	10.1766074	0.3509175				38.9422967	1.3428378				32.1038171	1.1070282			

Table 3b. GLM fit statistics for 2021.

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	78.90601191	78.90601191	224.86	<.0001	50.73168174	50.73168174	37.78	<.0001	303.7905517	303.790552	274.42	<.0001
Year	8	19.86699505	2.48337438	7.08	<.0001	31.73012688	3.96626586	2.95	0.0152	25.5099903	3.1887488	2.88	0.0173
Interaction (i.e., SurveyDay x year)	8	4.3799679	0.54749599	1.56	0.1803	18.93500142	2.36687518	1.76	0.126	5.1543147	0.6442893	0.58	0.7842

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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 3c. GLM estimates of deviations in model intercept used to calculate rate of change in water temperature, thickness and DO concentrations of the hypolimnion for years 2012-2020 compared to 2021 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 2021	10.03303	0.46322965	21.66	<.0001	9.4433845	0.90616153	10.42	<.0001	8.6312473	0.82276001	10.49	<.0001
Slope in 2021	0.0333851	0.00590161	5.66	<.0001	-0.0525582	0.01154463	-4.55	<.0001	-0.0808456	0.01048208	-7.71	<.0001
Difference in intercept in 2012[††]	1.3996426	0.82486648	1.7	0.1004	-5.7536089	1.613589	-3.57	0.0013	-2.7045558	1.4650771	-1.85	0.0751
Difference in intercept in 2013	-0.2353664	0.81987077	-0.29	0.7761	-3.4801212	1.60381649	-2.17	0.0383	0.109666	1.45620404	0.08	0.9405
Difference in intercept in 2014	-3.2412531	0.7098807	-4.57	<.0001	-0.9237849	1.38865589	-0.67	0.5112	3.3782223	1.26084644	2.68	0.012
Difference in intercept in 2015	-1.1185251	0.75308119	-1.49	0.1483	-1.9138418	1.47316392	-1.3	0.2041	1.7455087	1.33757649	1.3	0.2022
Difference in intercept in 2016	-2.527626	1.13388446	-2.23	0.0337	-2.0805366	2.21808442	-0.94	0.356	3.7104574	2.01393583	1.84	0.0757
Difference in intercept in 2017	0.3628312	0.74430506	0.49	0.6296	-2.4294346	1.4559962	-1.67	0.106	-0.6191409	1.32198887	-0.47	0.643
Difference in intercept in 2018	-2.4222732	0.71539092	-3.39	0.0021	-0.2600131	1.39943489	-0.19	0.8539	1.7022746	1.27063336	1.34	0.1907
Difference in intercept in 2019	-2.3272478	0.68006698	-3.42	0.0019	-4.3523155	1.33033482	-3.27	0.0028	0.5630951	1.20789313	0.47	0.6446

[**] Ratio of the Estimate to its Standard Error

[††] Factors are for the difference in the intercept from the reference (i.e., 2021) 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., 2021) and the specific year. For example, in 2014, the estimated temperature intercept (i.e., estimated value on the 160th Julian day) is 6.7918 ˚C (10.0330 -3.2413), and it is significantly different from the estimated temperature intercept in 2021 (i.e., 10.0330 ˚C) because the p-value is less than alpha = 0.05.

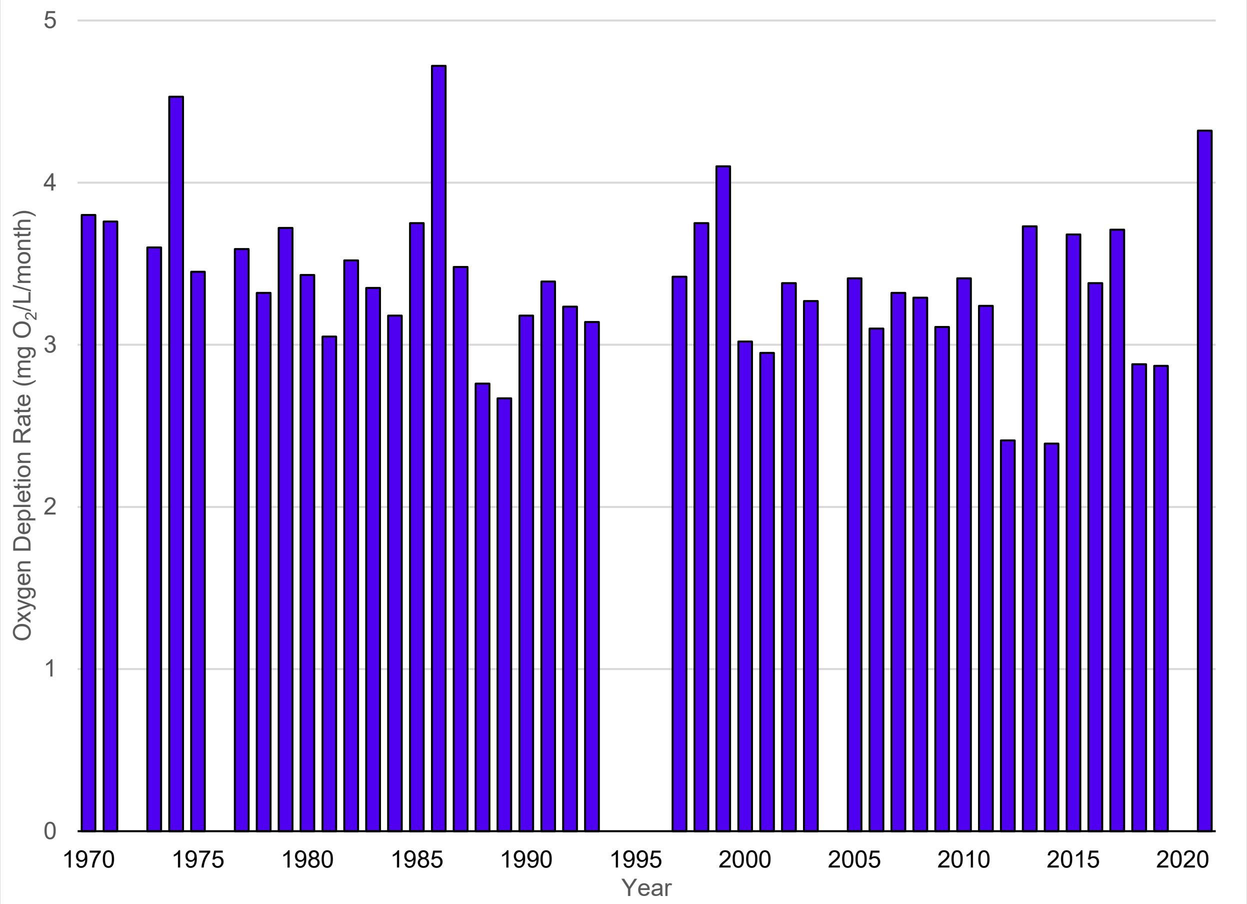

Figure 7. Annual DO depletion rate in the central basin of Lake Erie from 1970-2021.

7. CONCLUSIONS

The U.S. EPA GLNPO Lake Erie Dissolved Oxygen Monitoring Program monitored the oxygen and temperature profiles at 10 fixed stations in the central basin of Lake Erie from June – October 2021 to assess water quality trends and measure progress made in achieving water quality improvements. The 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).

The springtime conditions during 2021 and an elevated depletion rate, resulted in hypoxic and anoxic conditions occurring earlier in the season than on average. This increased the overall length of time that the bottom waters of Lake Erie were subjected to these conditions during this year.

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APPENDIX A - QUALITY CONTROL RESULTS

A summary of 2021 results not meeting acceptance criteria is provided in the table below.

Table A-1. Quality control (QC) scorecard of 2021 CTD-collected temperature and dissolved oxygen (DO) data not meeting acceptance criteria.

Survey	Issue	Cause	Decision	Corrective Actions
June 15	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.	Run additional replicate Winkler analyses until consistency is achieved.
June 29	Temperature accuracy check exceeded QC criterion (1 of 2 samples)	Temperature of the hull may be affecting the measurement from the hull-mounted transducer. Samples may not have been taken at the same depth.	Average temperature relative percent difference (RPD) for survey falls within QC criterion. Temperature values from CTD are considered valid.	Re-sample thermometer reading.
Sept. 9	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.	Run additional replicate Winkler analyses until consistency is achieved.
Oct 6-7	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.	Run additional replicate Winkler analyses until consistency is achieved.
	For samples with DO < 5 mg/L, the absolute difference between the SeaBird values and Winkler values exceeded the QC criterion (1 of 1 samples)	Due to a thin hypolimnion, thermocline or epilimnion water may have been present in the Winkler sample.	All samples where DO >5.00 mg/L were within QC criteria (3 of 3 samples). CTD DO values are considered valid.	Not Applicable