AQUATIC ECOSYSTEM
HEALTH & MANAGEMENT SOCIETY

MICHIGAN STATE UNIVERSITY PRESS

Supplementary Material
Nutrient and environmental factors regulating western Lake Erie cyanobacterial blooms

Hounshell, A.G.[1], Johnson, L.T.[2], Stumpf, R.P.[3]

[1] National Centers for Coastal Ocean Science, National Oceanic and Atmospheric Administration, 101 Pivers Island Rd., Beaufort, NC, 28516; alexandria.hounshell@noaa.gov

[2] National Center for Water Quality Research, Heidelberg University, 310 E. Market St., Tiffin, OH, 44883; ljohnson@heidelberg.edu

[3] National Centers for Coastal Ocean Science, National Oceanic and Atmospheric Administration, 1305 East-West Highway, Silver Spring, MD, 20910; richard.stumpf@noaa.gov

The supplementary information contains 7 Figures and 4 Tables.

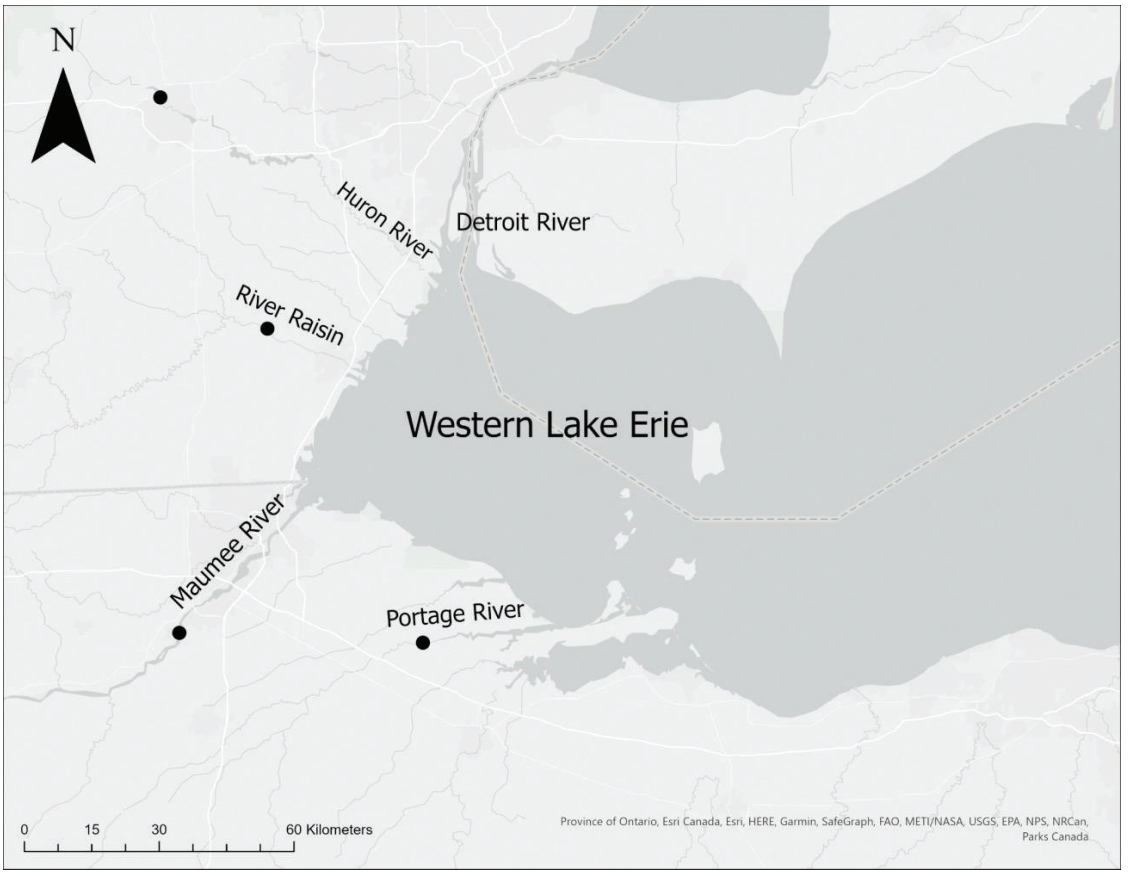

Figure S1. Map of western Lake Erie showing the Detroit river and the primary tributaries to western Lake Erie (Huron, Raison, Maumee, and Portage rivers). Dots show the location of USGS gauges used to estimate freshwater flow from the four largest primary tributaries (Table S1).

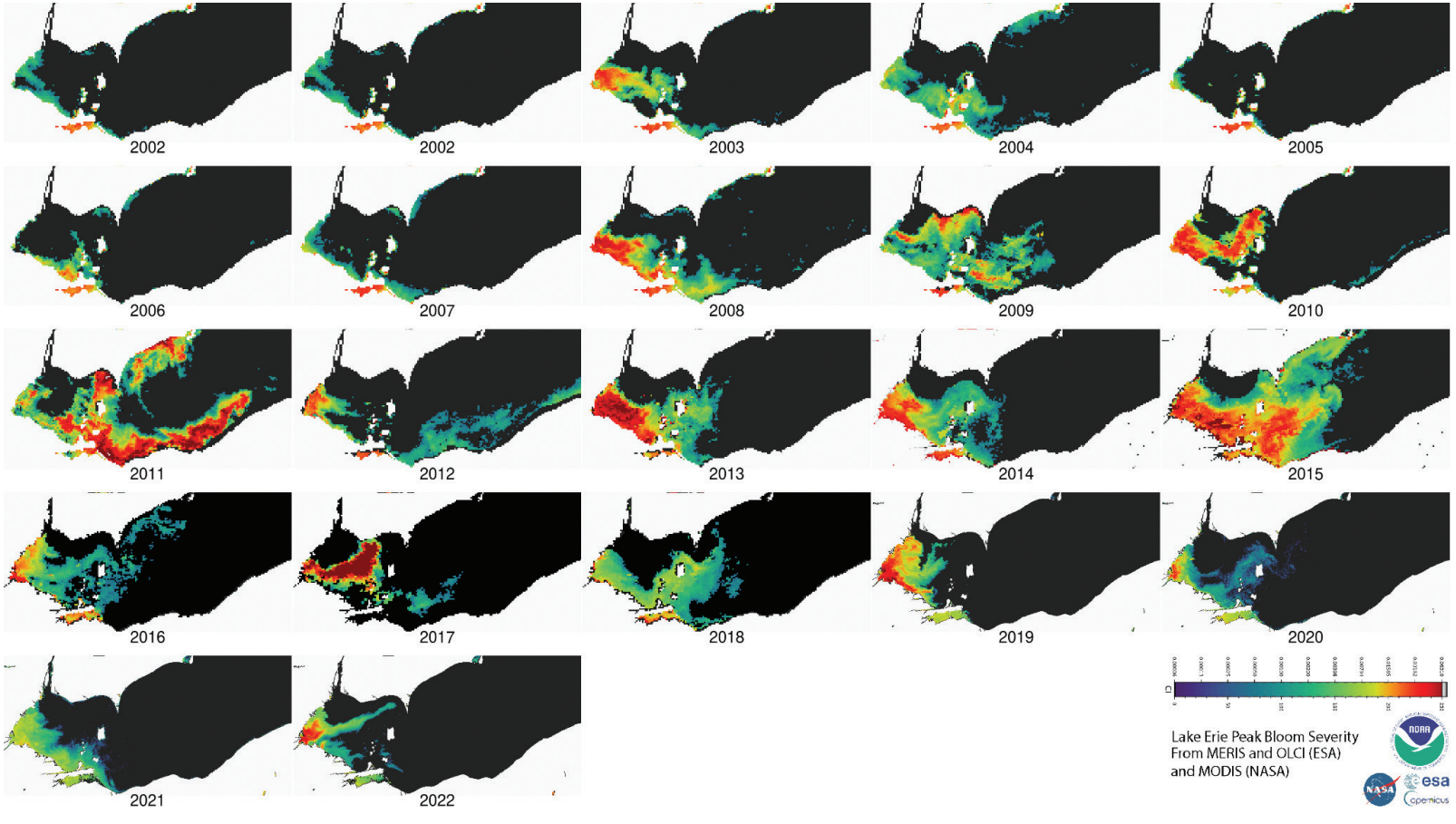

Figure S2. Maximum 10-day composites for western Lake Erie for each year from 2002-2022 obtained from satellite remote sensing imagery. Satellite remote sensing imagery was obtained from the Medium Resolution Imaging Spectrometer (MERIS) for 2002-2011, the Moderate Resolution Imaging Spectroradiometer (MODIS) from 2012-2018, and the Sentinel-3 Ocean and Land Colour Instrument (OLCI) from 2019-2022. Figure courtesy of T. Briggs.

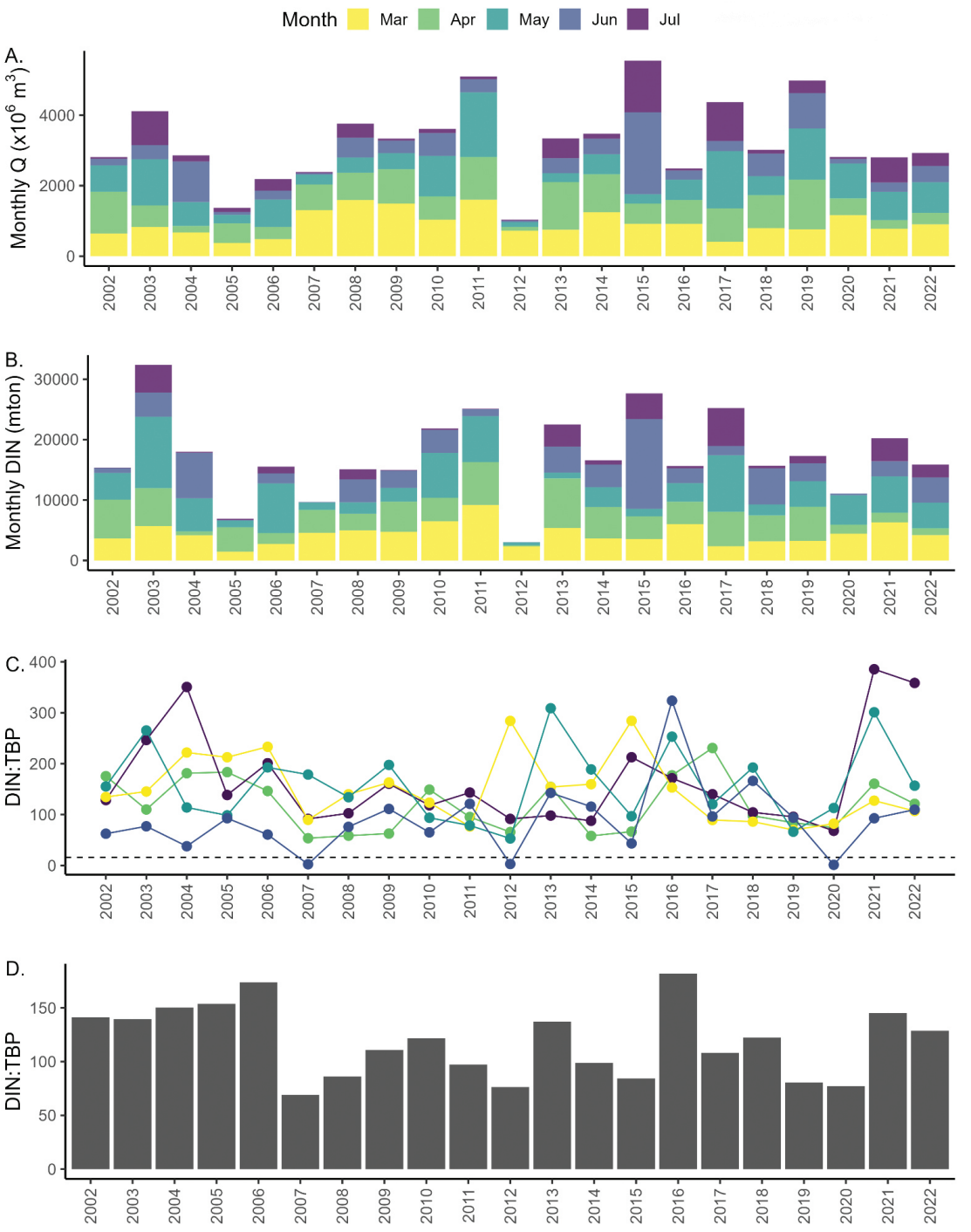

Figure S3. Monthly freshwater discharge and various nutrient loading parameters for the Maumee river from 2002-2022, including A) Freshwater discharge (Q, x10^6 m^3) plotted by month (March-July); B) Monthly Dissolved Inorganic Nitrogen (DIN) loading from March-July (mton); C) DIN:TBP molar ratios plotted for each month (March-July); and D) Spring DIN:TBP molar ratios. The dashed horizontal line in panel C corresponds to the Redfield Ratio (1:16).

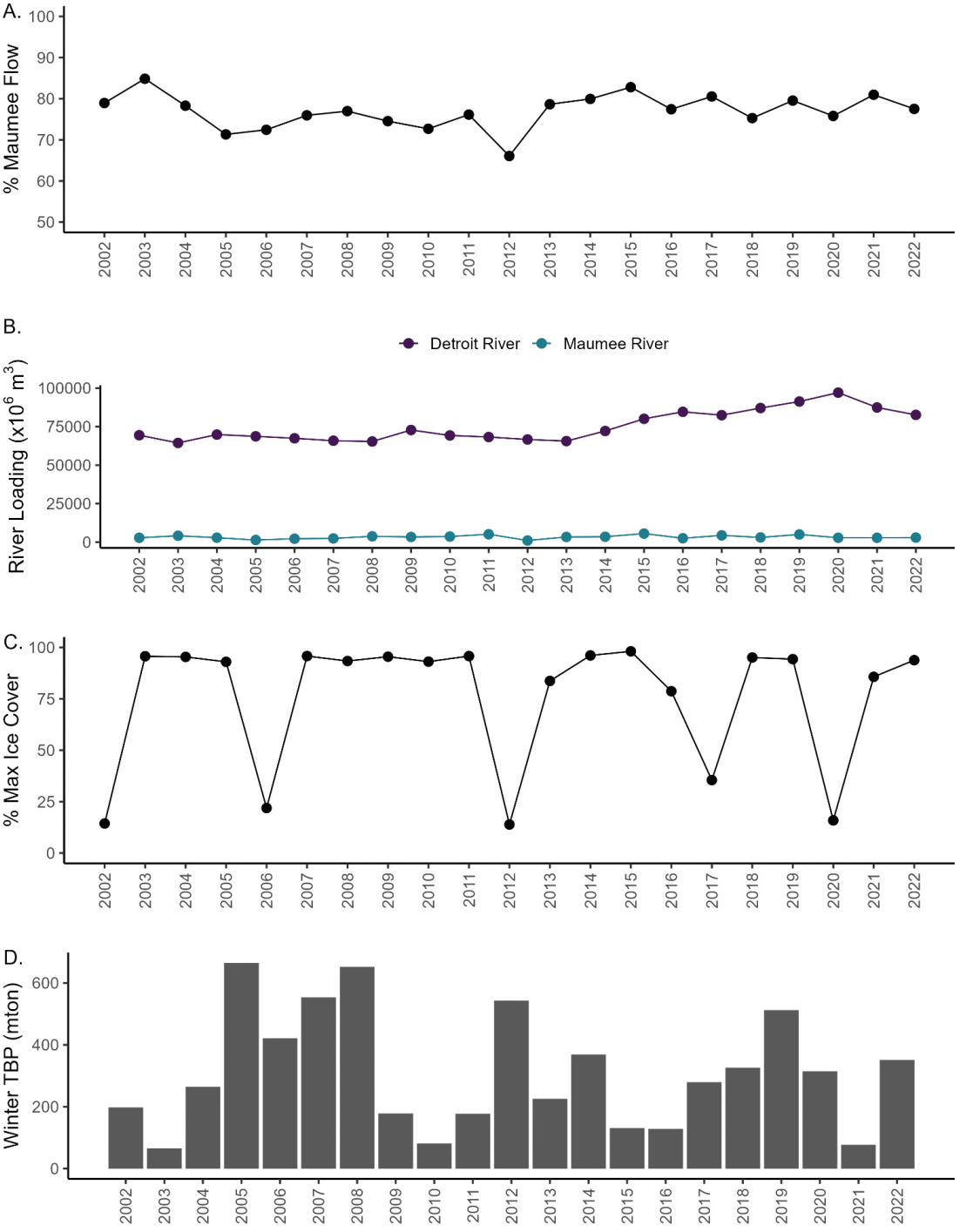

Figure S4. Additional environmental parameters used to characterize the physical and nutrient environment of the western Lake Erie basin including A) Percent of Maumee river flow calculated using USGS flow information for each of the main river basins (Huron, Raisin, Maumee, Portage rivers); B) Total Spring (March-July) Detroit and Maumee river loading ($x10^6$ m^3) obtained from the U.S. Army Corps of Engineers and USGS, respectively; C) Percent of maximum ice cover for the preceding winter; and D) Winter (November-February) total bioavailable phosphorus (TBP) loading for the Maumee river.

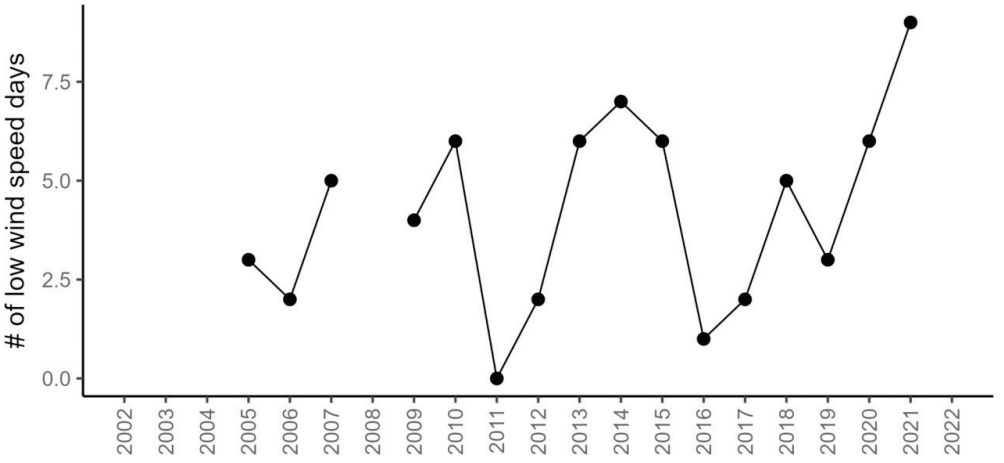

Figure S5. Number of low wind speed days (<3 m s^{-1}) for each year as calculated from the Toledo Light meteorological data. No data exists for 2002, 2003, 2004, or 2008.

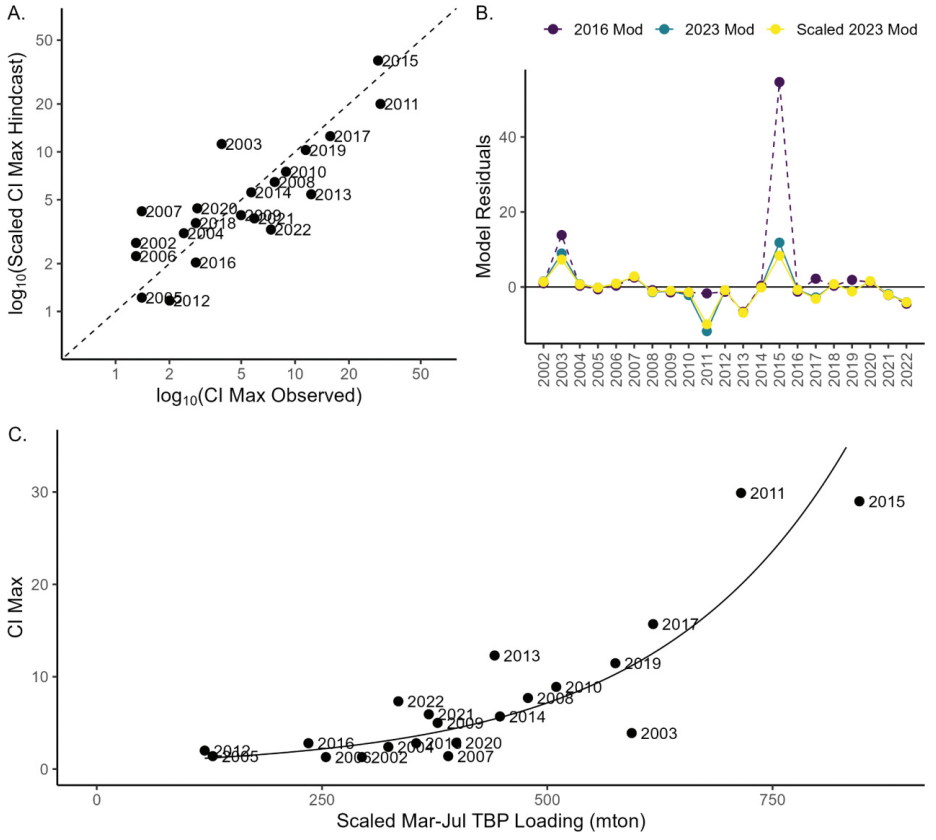

Figure S6. Results for the spring total bioavailable phosphorus (TBP) model to predict cyanobacterial index (CI) max using TBP loading scaled to the proportion of Maumee river load. A) Scaled results for observed CI max versus hindcast (modeled) CI max. B) Model residuals (modeled-observed) for the Stumpf et al. (2016) model (2016 mod), the updated 2023 model (2023 mod), and the scaled 2023 mod (scaled 2023 mod). C) Identified relationship between scaled March-July TBP loading (mton) and CI max. The scaled TBP values were calculated by multiplying the Maumee spring TBP loading by the percent of loading not accounted for by the Maumee river following: scaled TBP = Maumee TBP loading + (Maumee TBP loading*(100-Percent of Maumee River Flow)/100).

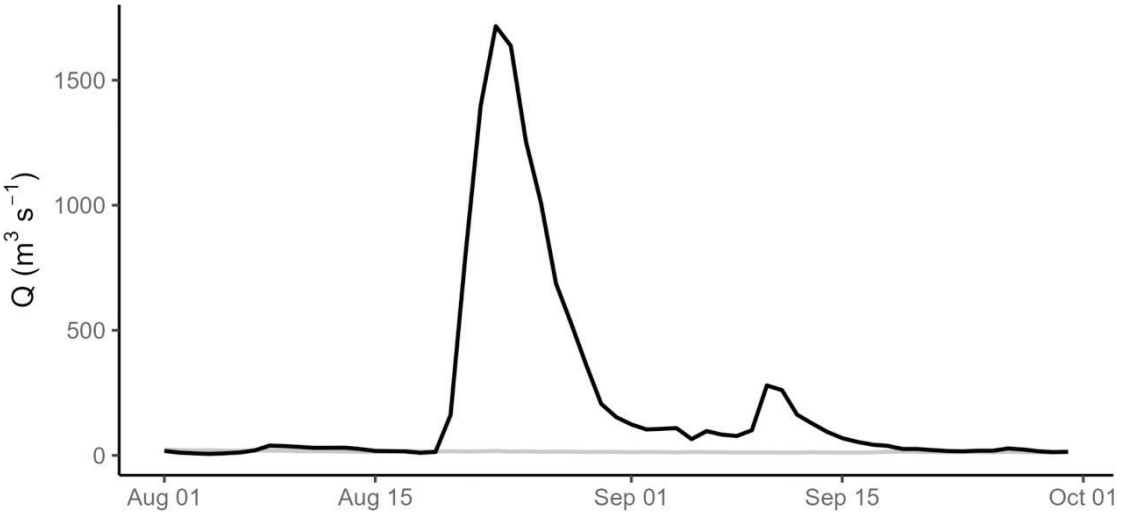

Figure S7. USGS discharge (Q, $m^3 s^{-1}$) measured on the Maumee river at Waterville, Ohio for 1 August 2007 to 30 September 2007 (black line) and the long term median (1988-2022; gray line).

Table S1. USGS gaging station information used to calculate the proportion of Maumee River flow into the western basin of Lake Erie, including information on the area of gaged to ungaged watershed for each station.

River	USGS Gaging Station	Location	Area of gaged watershed (mi2)	Area of ungaged watershed (mi2)	Watershed scaling factor
Huron	04174500	Huron river at Ann Arbor, MI	729	908	1-(729/908)
Raisin	04176500	Raisin river near Monroe, MI	1,042	1,072	1-(1042/1072)
Maumee	04193500	Maumee river at Waterville, OH	6,330	8,316	1-(6330/8316)
Portage	04195820	Portage river near Elmore, OH	494	766	1-(494/766)

Table S2. Table of Pearson's rho (ρ) calculated for each environmental variable. Collinear variables (Pearsons correlation coefficient, ρ>0.70) were removed from subsequent analyses (shaded).

	Q Mar	Q Apr	Q May	Q Jun	Q Jul	Q Mar-Jul	TBP Mar	TBP Apr	TBP May	TBP Jun	TBP Jul	TBP Mar-Jul	TBP Nov-Feb
CI Max	0.34	0.58	0.79	0.30	0.28	0.80	0.36	0.46	0.78	0.26	0.24	0.83	-0.38
Q Mar		0.35	0.11	0.08	-0.52	0.37	0.97	0.24	0.06	0.11	-0.51	0.39	-0.35
Q Apr			0.39	0.63	0.10	0.79	0.32	0.92	0.29	0.53	0.01	0.71	-0.12
Q May				0.48	0.39	0.83	0.12	0.17	0.97	0.49	0.38	0.82	-0.35
Q Jun					0.07	0.70	0.01	0.49	0.33	0.97	-0.01	0.55	-0.24
Q Jul						0.32	-0.47	0.11	0.51	0.01	0.99	0.39	-0.23
Q Mar-Jul							0.35	0.60	0.77	0.65	0.28	0.96	-0.42
TBP Mar								0.24	0.08	0.02	-0.46	0.40	-0.21
TBP Apr									0.11	0.41	0.02	0.60	-0.01
TBP May										0.35	0.51	0.80	-0.37
TBP Jun											-0.06	0.53	-0.27
TBP Jul												0.36	-0.24
TBP Mar-Jul													-0.40

	DIN Mar	DIN Apr	DIN May	DIN Jun	DIN Jul	DIN Mar-Jul	DIN:TBP Mar	DIN:TBP Apr	DIN:TBP May	DIN:TBP Jun	DIN:TBP Jul	DIN:TBP Mar-Jul
CI Max	0.59	0.66	0.51	0.02	0.28	0.73	0.10	-0.06	-0.53	-0.26	0.07	-0.26
Q Mar	0.68	0.30	-0.08	0.09	-0.48	0.17	-0.66	-0.14	-0.34	0.01	0.04	-0.42
Q Apr	0.23	0.93	-0.01	0.46	0.12	0.54	-0.16	-0.47	-0.65	-0.01	0.29	-0.29
Q May	0.38	0.36	0.83	0.04	0.32	0.73	0.24	0.10	-0.61	-0.39	0.05	-0.16
Q Jun	0.14	0.43	0.20	0.71	0.02	0.48	-0.13	-0.20	-0.55	-0.13	0.21	-0.15
Q Jul	-0.14	0.18	0.51	0.07	0.99	0.56	0.65	0.39	-0.25	0.25	-0.03	0.13
Q Mar-Jul	0.46	0.72	0.53	0.37	0.30	0.82	-0.01	-0.10	-0.79	-0.14	0.17	-0.30
TBP Mar	0.65	0.27	-0.09	-0.05	-0.44	0.12	-0.71	-0.14	-0.36	-0.03	-0.12	-0.53
TBP Apr	0.15	0.92	-0.15	0.43	0.16	0.44	-0.13	-0.56	-0.52	0.08	0.16	-0.29
TBP May	0.36	0.31	0.87	-0.03	0.44	0.75	0.34	0.17	-0.59	-0.35	-0.02	-0.15
TBP Jun	0.15	0.34	0.26	0.69	-0.04	0.45	-0.11	-0.25	-0.53	-0.22	0.14	-0.18
TBP Jul	-0.15	0.10	0.54	0.03	0.98	0.53	0.64	0.42	-0.21	0.25	-0.06	0.13
TBP Mar-Jul	0.49	0.69	0.57	0.27	0.38	0.83	0.00	-0.09	-0.81	-0.14	0.01	-0.40
TBP Nov-Jan	-0.74	-0.21	-0.44	-0.50	-0.27	-0.73	-0.27	-0.46	0.33	-0.46	-0.48	-0.32
DIN Mar		0.32	0.28	0.16	-0.10	0.58	-0.07	0.28	-0.43	0.23	0.29	0.03
DIN Apr			0.05	0.36	0.23	0.62	0.06	-0.40	-0.58	0.08	0.32	-0.14
DIN May				-0.02	0.43	0.70	0.45	0.38	-0.30	-0.16	-0.04	0.17
DIN Jun					0.11	0.46	-0.04	-0.06	-0.37	0.42	0.44	0.17
DIN Jul						0.56	0.64	0.34	-0.24	0.33	0.03	0.13
DIN Mar-Jul							0.38	0.22	-0.64	0.23	0.30	0.13
DIN:TBP Mar								0.38	0.00	0.19	0.34	0.66
DIN:TBP Apr									0.03	0.48	0.11	0.50
DIN:TBP May										-0.03	-0.20	0.29
DIN:TBP Jun											0.44	0.53
DIN:TBP Jul												0.59

	Winter SST	Spring SST	Summer SST	% Maumee River	Detroit River Q (Mar-Jul)	Max Ice Cover	DOY Max. Ice	Low Wind Speed
CI Max	-0.07	-0.34	-0.20	0.36	0.00	0.16	-0.16	-0.30
Q Mar	-0.33	0.06	-0.27	0.11	-0.23	0.54	-0.09	0.05
Q Apr	-0.60	-0.64	-0.28	0.56	0.16	0.54	0.30	-0.05
Q May	0.14	-0.26	-0.12	0.41	0.34	0.03	0.02	-0.32
Q Jun	-0.24	-0.20	-0.16	0.39	0.52	0.40	0.36	0.15
Q Jul	0.18	-0.48	-0.09	0.58	0.36	-0.31	0.22	0.18
Q Mar-Jul	-0.25	-0.49	-0.29	0.65	0.35	0.37	0.22	-0.06
TBP Mar	-0.32	0.03	-0.26	0.10	-0.28	0.49	-0.06	0.04
TBP Apr	-0.70	-0.53	-0.28	0.50	-0.06	0.51	0.35	0.13
TBP May	0.20	-0.23	-0.11	0.41	0.29	-0.05	-0.05	-0.28
TBP Jun	-0.18	-0.01	-0.16	0.28	0.45	0.38	0.25	0.17
TBP Jul	0.23	-0.42	-0.10	0.55	0.34	-0.37	0.19	0.17
TBP Mar-Jul	-0.25	-0.42	-0.32	0.64	0.21	0.33	0.18	0.01
TBP Nov-Jan	-0.08	0.02	0.05	-0.41	-0.24	-0.22	0.05	-0.23
DIN Mar	-0.08	0.00	0.08	0.28	-0.06	0.45	-0.08	0.06
DIN Apr	-0.63	-0.65	-0.25	0.54	-0.02	0.52	0.18	-0.06
DIN May	0.25	-0.04	-0.22	0.30	0.17	-0.25	0.12	-0.17
DIN Jun	-0.38	-0.08	-0.15	0.40	0.41	0.40	0.33	0.47
DIN Jul	0.15	-0.49	-0.08	0.59	0.32	-0.29	0.19	0.21
DIN Mar-Jul	-0.17	-0.39	-0.22	0.68	0.26	0.22	0.23	0.10
DIN:TBP Mar	0.24	-0.26	0.34	0.22	0.21	-0.25	-0.02	-0.11
DIN:TBP Apr	0.28	-0.09	0.28	0.27	0.34	-0.05	0.11	0.31
DIN:TBP May	0.34	0.45	-0.14	-0.70	-0.49	-0.60	-0.21	-0.13
DIN:TBP Jun	-0.27	-0.29	0.11	0.48	0.14	0.18	0.44	0.52

	Winter SST	Spring SST	Summer SST	% Maumee River	Detroit River Q (Mar-Jul)	Max Ice Cover	DOY Max. Ice	Low Wind Speed
DIN:TBP Jul	-0.11	-0.40	0.41	0.39	0.46	0.29	0.12	-0.18
DIN:TBP Mar-Jul	0.03	-0.09	0.33	0.04	0.11	-0.10	0.20	-0.03
Winter SST		0.39	0.20	-0.38	0.17	-0.73	-0.48	-0.39
Spring SST			-0.06	-0.75	-0.40	-0.31	-0.42	0.07
Summer SST				0.02	0.42	0.19	-0.15	-0.09
% Maumee River					0.55	0.41	0.60	0.35
Detroit River Q (Mar-Jul)						0.17	0.22	0.10
Max Ice Cover							0.22	0.40
DOY Max. Ice								0.40

Table S3. All variables (CI max, bloom severity, and environmental variables) used for logarithmic and logistic regression including: CI Max, bloom severity (Severity), bloom size as low (Severity<5) or high (Severity>5); July total bioavailable phosphorus (TBP) loading (mton); Spring (March-July) TBP Loading; Winter (November-February) TBP loading; July dissolved inorganic nitrogen (DIN) to TBP molar ratios; Spring DIN:TBP; Winter sea surface temperature (SST, °C); Spring SST; Summer SST; Detroit river Flow (m^3); Percent of maximum ice cover during the preceding winter; day of year (DOY) of maximum ice extent; and number of low wind speed (<3 m s^{-1}) days during July-August. Rows in gray were excluded from multiple linear regression modeling due to missing data (NA).

Year	CI Max	Severity	Bloom Size	TBP Jul	TBP Mar-Jul	TBP Nov-Feb	DIN: TBP Jul	DIN: TBP Mar-Jul	Winter SST	Spring SST	Summer SST	Detroit River	Max Ice Cover	DOY Max. Ice	Low Wind Speed
2002	1.3	0.3	Low	2	243	198	63	141	NA	NA	NA	$2.27x10^9$	14	3	NA
2003	3.9	4.1	Low	131	516	65	77	140	NA	15.9	21.9	$2.11x10^9$	96	27	NA
2004	2.4	2.7	Low	10	266	265	38	150	2.2	16.7	21.6	$2.28x10^9$	95	33	NA
2005	1.4	0.3	Low	5	100	665	93	154	1.9	17.3	23.6	$2.25x10^9$	93	38	3
2006	1.3	1.3	Low	41	199	421	61	174	2.9	18.2	21.8	2.20x10	22	61	2
2007	1.4	0.9	Low	2	314	554	3	69	2.0	17.8	23.0	$2.15x10^9$	96	50	5
2008	7.7	6.2	High	48	389	652	76	86	1.9	17.2	21.8	$2.14x10^9$	93	70	NA
2009	5.0	5.1	High	2	302	178	111	111	2.3	17.3	21.4	$2.38x10^9$	96	36	4
2010	8.9	5.8	High	8	400	81	65	122	2.7	19.3	22.4	$2.26x10^9$	93	39	6
2011	29.9	10.0	High	1	577	178	121	97	2.3	17.4	22.5	$2.23x10^9$	96	32	0
2012	2.0	2.9	Low	1	89	543	3	76	4.3	19.3	22.5	$2.18x10^9$	14	21	2
2013	12.3	8.5	High	57	364	226	143	137	1.7	16.8	22.1	$2.14x10^9$	84	53	6
2014	5.7	6.6	High	14	373	369	116	99	1.2	17.4	21.5	$2.36x10^9$	96	65	7
2015	29.0	10.5	High	216	722	131	43	84	NA	15.9	22.1	$2.62x10^9$	98	49	6
2016	2.8	3.2	Low	3	192	128	324	182	3.2	17.3	24.2	$2.77x10^9$	79	46	1
2017	15.7	8.0	High	144	517	279	96	108	3.3	16.7	22.2	$2.69x10^9$	36	39	2
2018	2.8	3.6	Low	6	284	326	166	122	2.0	18.1	23.2	$2.85x10^9$	95	40	5
2019	11.5	8.5	High	29	478	513	94	81	2.6	16.6	22.7	$2.98x10^9$	94	61	3
2020	2.9	3.3	Low	4	321	315	1	77	2.6	16.8	NA	$3.17x10^9$	16	60	6
2021	5.9	5.6	High	90	310	77	93	145	3.1	17.5	23.5	$2.86x10^9$	86	51	9
2022	7.3	6.8	High	42	273	351	110	129	1.3	15.3	24.4	$2.70x10^9$	94	31	NA

Table S4. Table of minimum, maximum, mean, standard deviation (St. dev.), and median for selected environmental parameters including: Winter (November-February) total bioavailable phosphorus (TBP) loading (mton); Spring (March-July) TBP loading; July TBP loading; Spring dissolved inorganic nitrogen (DIN) loading (mton); Spring DIN:TBP molar ratios; July DIN:TBP molar ratios; Winter sea surface temperature (SST, °C); Spring SST; Summer SST; proportion of Maumee River flow; maximum winter ice cover (%); and day of year (DOY) of maximum ice extent.

	Minimum	Maximum	Mean	St. dev.	Median
Winter TBP (mton)	65.5	665.1	310.3	187.7	279.4
Spring TBP (mton)	89.4	722.1	344.2	154.7	314.4
Jul. TBP (mton)	1.3	215.6	40.7	58.3	9.7
Spring DIN (mton)	3081	32484	17488	6881	15984
Spring DIN:TBP	69	182	118	33	122
Jul. DIN:TBP	1	324	90	69	93
Winter SST (oC)	1.20	4.34	2.42	0.76	2.3
Spring SST (oC)	15.29	19.28	17.23	1.00	17.3
Summer SST (oC)	21.40	24.41	22.55	0.88	22.4
Proportion Maumee Flow (%)	66	85	77	4	77.4
Max Ice Cover (%)	14	98	75	32	93
DOY Max. Ice	3	70	43	16	40