Recent patterns in Lake Erie phosphorus concentrations in response to changing loads

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KEYWORDS

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ABSTRACT

Despite the initial success of extensive efforts to reduce phosphorus (P) loading to Lake Erie as part of the Great Lakes Water Quality Agreement, Lake Erie appears to be undergoing a re-eutrophication and is plagued by harmful algal blooms. To offer insights into potential lake responses under differing Maumee River loads and reveal recent changes with time, we explored patterns in phosphorus and chlorophyll *a* data from 2008–2018 collected in western Lake Erie near the mouth of the Maumee River. We found high, but relatively stable Maumee River and lake concentrations of total P (TP) and soluble reactive P (SRP) with no discernable annual or seasonal patterns. Maumee spring TP load was not strongly related to lake TP, and lake SRP concentrations were positively but weakly related to SRP loads. Lake TP was a strong predictor of chlorophyll *a*, but the relationship was weaker at sites closer to the Maumee. These results highlight spatial differences both in P concentration and the relationship between TP and chlorophyll *a*, and indicate that spring phosphorus loads are a weak algal biomass predictor in the portion of the western basin of Lake Erie represented by these sampling stations.

INTRODUCTION

In the 1960s Lake Erie became infamous for poor water quality and was widely reported to be dying (The Economist 1965, Sweeney 1993), generating concerns of irreversible damage (Hartman 1972). In response, Canada and the United States established total phosphorus (TP) load targets to mitigate the severe anthropogenic eutrophication conditions that were a problem throughout the Great Lakes. Lake Erie's target TP load was 11,000 metric tonnes yr^{-1}, a 55% reduction from the estimated 1976 load (International Joint Commission [IJC] 1978). Under these new restrictions water quality improved, and the problem was considered solved (De Pinto et al. 1986, Makarewicz and Bertram 1991, Ludsin et al. 2001).

Paradoxically, since the early 2000s, Lake Erie has again become plagued by harmful algal blooms (HABs) despite the fact that TP loads have met the target in most years (Baker et al. 2014). In 2011, for example, Lake Erie experienced a record bloom despite meeting the 1978 target (Michalak et al. 2013). Subsequently, in 2014 the city of Toledo, Ohio issued a do-not-drink advisory when toxins found in treated water were traced back to high toxin concentrations in the intake water due to a *Microcystis* bloom (Steffen et al. 2017). Furthermore, in the past few years both Michigan and Ohio have declared the open waters of western Lake Erie as impaired due to HABs as per the Clean Water Act (Davis et al. 2019). Recognizing the resurgent problem, Canada and the United States proposed lower phosphorus targets, which became effective in 2016. These new targets focus on inputs from the Maumee River (Figure 1), considered the main driver of HABs in Lake Erie's western basin, and include spring (March–July) limits for both total phosphorus (860 metric tons) and dissolved reactive phosphorus (186 metric tonnes) (Annex 4 Report 2015).

To better understand the response of western Lake Erie to yearly differences in spring phosphorus load we analyzed phosphorus and chlorophyll *a* concentration data collected over an approximately 300 km^2 region (Figure 1) near the mouth of the Maumee River by the National Oceanic and Atmospheric Administration Great Lakes Environmental Research Laboratory (NOAA GLERL) and the University of Michigan Cooperative Institute for Great Lakes Research (CIGLR). These data reveal changes during the recent period of re-eutrophication and, when compared with Maumee River data, offer insights into the effect of differing phosphorus inputs. Our results will help guide expectations as management actions are implemented throughout the watershed to meet the new phosphorus targets.

MATERIALS AND METHODS

Maumee River data collection. Maumee River flow and nutrient concentration data have been collected nearly continuously by the National Center for Water Quality Research (NCWQR) at Heidelberg University and the USGS since 1974. NCWQR collects water 5.6 km upstream of the USGS stream gage at Waterville (USGS #04193500). Details on lab analysis for Maumee River samples can be found in Baker et al. (2014).

Western Lake Erie data collection. We collected surface (0.75 m) samples at set stations (Table 1, Fig. 1) from western Lake Erie from spring (April–May) until fall (October–November) from 2008–2018. Additional "bloom chasing" samples were collected in 2008–2013 to target large *Microcystis* blooms. Weekly sampling stations were not set until 2009, so we present the 2008 data plus the bloom chasing samples as site "other" and do not include it in the violin plots showing concentration data over time at set sampling stations. Samples were taken with a modified clean Niskin bottle (Fahnenstiel et al. 2002), poured into acid-washed 4 L Nalgene containers, stored in coolers, and brought to GLERL for immediate processing.

Chlorophyll *a* (chl *a*) samples were filtered onto Whatman GF/F filters (0.7 µm nominal pore size) and frozen until extraction the next day. Two replicate filters were extracted with N, N-dimethylformamide (Speziale et al. 1984) and analyzed on a Turner Designs fluorometer calibrated with commercial chl *a* standards.

Two replicate raw water samples for total phosphorus (TP) were collected from each site. Total phosphorus samples were digested by the persulfate oxidation method and stored at room temperature until analysis. Two replicates were filtered through a 0.2 µm nylon filter for soluble reactive phosphorus (SRP) and frozen until analysis. TP and SRP concentrations were determined on a SEAL QuAAtro or AA3 autoanalyzer (SEAL Analytical Inc., Mequon, WI USA) using standard colorimetric procedures (APHA 1998) as detailed by the instrument manuals.

Statistical analysis. We estimated multilevel/partially pooled Bayesian hierarchical models of Maumee River loads vs. lake P and chl *a* vs. TP where slope and intercept differed by station using the 'rstanarm' package (Goodrich et al. 2018) in R (R Core Team, 2018). Partial pooling combines information from all stations such that parameters for a given station can be estimated when only a few observations are available (Stow et al. 2009, Qian 2017). We used diffuse normal prior distributions with a mean of zero. We ran three chains for 10,000 iterations and discarded the first half as warm-up to obtain 15,000 simulations for analysis. We confirmed convergence using Gelman-Rubin statistic (R-hat <1.01; Gelman and Hill 2006) and by examining traceplots. None of the models had influential outliers as assessed by leave-one-out cross-validation ('loo') in the 'rstan' package (Stan Development Team 2018).

RESULTS

Maumee River TP concentrations were highly variable by about an order of magnitude, but fairly consistent in range and average from 2009–2018 (Figure 2, top panel). For every year except 2012, the median (160–250 μg L^{-1}) and average (200–280 μg L^{-1}) daily TP concentrations were similar. A higher frequency of low concentrations was observed in 2012 than for other years resulting in a lower median (140 μg L^{-1}) and average (180 μg L^{-1}). There was no discernible monthly pattern; in some years the highest concentrations occurred in March and April (e.g., 2009, 2012, 2013) while in some years March and April exhibited the lowest concentrations (e.g., 2010, 2017, 2018).

Lake TP concentrations were variable within a year but showed only slight year-to-year variability, although data at some sites was insufficient to draw any conclusions regarding changes with time (Figure 2, bottom panel). Concentrations were generally related to distance from the mouth of the Maumee River; the highest average concentrations occurred at Sites WE06 (average ± SD = 114 ± 129 μg L^{-1}) and WE09 (158 ± 119 μg L^{-1}), which are 6.9 and 4.5 km, respectively, from the river mouth (Table 1, Figure 1). Conversely, the lowest TP concentrations occurred at sites WE03 (27.4 ± 12.9 μg L^{-1}), WE04 (24.0 ± 15.4 μg L^{-1}), and WE05 (28.1 ± 17.5 μg L^{-1}), which are 25.0, 27.1, and 21.0 km, respectively, from the river mouth. There were no discernable patterns with lake TP and sampling month (Figure 2, bottom panel).

Maumee River spring TP loads ranged from 393–2,318 metric tonnes (2012 and 2011, respectively; Figure 3). Lake TP concentrations ranged from 1.8–2,482 μg L^{-1}. The relationship between spring TP load and lake TP across all sites and years was likely positive, though the 95% credible interval included negative values (slope = 0.008 [-0.009, 0.026]; mean and 95% credible interval [CRI]; Figure 3). The slopes differed among sites, but there was high uncertainty in the model. Only three sites (WE06, WE08, and WE09) had strictly positive CRIs (Figure 3).

Maumee River SRP concentrations varied over two orders of magnitude, but had no discernable inter-annual patterns from 2009–2018 (Figure 4, top panel). Similar to TP, 2012 had lower average (37 μg L^{-1}) and median (35 μg L^{-1}) SRP than the annual medians (45–87 μg L^{-1}) and averages (45–86 μg L^{-1}) from all other years. There was no discernable monthly pattern; in some years the highest concentrations happened in March and April (e.g., 2011, 2012), whereas in March and April had the lowest concentrations in other years (e.g., 2015, 2017).

Lake SRP was variable across sites and among years, with no consistent temporal patterns (Figure 4, bottom panel). Sites WE06 (average ± SD = 19.7 ± 27.9 μg L^{-1}) and WE09 (29.7 ± 29.5 μg L^{-1}) had the highest average SRP concentrations, similar to what was observed in TP. The lowest concentrations were at sites WE03, WE04, and WE05 (average ± SD of 1.9 ± 2.4, 2.5 ± 3.4, and 2.0 ± 2.8 μg L^{-1}, respectively). There were no consistent patterns in SRP concentrations and sampling month.

Spring SRP loads ranged from 64–610 metric tonnes (2012 and 2015, respectively; Figure 5) and lake SRP concentrations ranged from 0.04–135 μg L^{-1}. Across all sites and years there was an overall positive relationship between spring SRP load and lake SRP (slope = 0.021 [0.004, 0.037]; Figure 5). Unlike TP, the site-specific slope estimates were all positive (Figure 5), although most 95% credible intervals included negative values. Five sites (WE02, WE06, WE08, WE09, and WE12) had strictly positive CRIs. Sites WE06 and WE09 had the strongest relationships with SRP spring load (slope = 0.052 [0.037, 0.676] and slope = 0.066 [0.046, 0.086], respectively), and sites WE03 (slope = 0.006 [-0.012, 0.029]), WE04 (slope = 0.004 [-0.011, 0.018], and WE05 (slope = 0.008 [-0.014, 0.030]) the weakest (Figure 5). |

We observed a large range of chl *a* and TP concentrations, and sites with higher TP tended to have higher chl *a* (Table 1). We found support for a strong, positive relationship between chl *a* and TP for all sites together (slope = 0.793 [0.563, 1.035]; Figure 6), and at individual sites (Figure 6, inset). The credible intervals were generally overlapping, indicating weak differentiation among stations. The relationship was strongest at sites WE08 (slope = 1.257 [1.024, 1.497]) and WE15 (slope = 1.191 [0.747, 1.667], Figure 6). Site WE15 is the farthest site from the Maumee (Table 1), while WE08 is closer to the River Raisin than most sites. Conversely, sites WE06, WE09, and WE12 had lower slopes and a higher intercept, suggesting higher TP and chl *a* overall (Table 1), but a weak response of algal biomass to TP (Figure 6). These three sites lie almost directly at the mouth (WE09 and WE06), or along the southern shore (WE12, Figure 1). The bloom-chasing ("other") samples were very similar to the overall estimates (Figure 6).

DISCUSSION

The establishment of phosphorous load targets to control eutrophication was revolutionary in the 1970s, arising from a body of work by Richard Vollenweider that produced the "phosphorus loading concept". This concept is based on the premise that P loading influences lake P concentrations, and higher P concentrations lead to higher primary production (Vollenweider and Dillon 1974). We found that, despite large differences in Maumee River spring loads, western Lake Erie exhibited highly variable phosphorus concentrations from 2008–2018 with no discernable trends. While our results did demonstrate a consistent positive relationship between lake TP and chlorophyll *a*, the overall weak relationship between load and lake phosphorus concentration indicates that spring phosphorus loads are a poor algal biomass predictor in this portion of western Lake Erie.

Our results highlighted spatial differences in phosphorus concentration; sampling stations generally reflected Maumee River concentrations based on proximity to the river mouth. Larson et al. (*in revision*) showed a similar pattern, reflecting the gradient between very low concentrations entering from the Detroit River to the north and the high Maumee River concentrations from the south. The high Maumee phosphorus concentrations may promote western basin cyanobacterial dominance. The probability of cyanobacteria becoming dominant in experiments increases to about 80% at TP of 0.1 mg L^{-1} (Downing et al. 2001), and experimental *Microcystis* growth plateaus at 0.22 mg L^{-1} TP with sufficient light and nitrogen (Baldia et al. 2007). In our analysis, Maumee River concentrations were on average ~0.2 mg L^{-1} TP in the spring, and the lake sites closer to the Maumee (e.g., WE06 and WE09) frequently had TP concentrations in this range.

The relationship between TP and algal biomass (as chl *a*) also depended on proximity to the Maumee River. Stations WE06 and WE09, near the mouth of the river, which exhibited the strongest TP load to lake TP concentration-response (Figure 4), exhibited the weakest chl *a* – TP relationship (Figure 6). Conversely, stations farther away (e.g., WE04 and WE05), which had minimal TP load-response relationships had stronger, better defined chl *a* – TP relationships. This decoupling at stations closer to the Maumee could result from several factors: vertical migration of cells/colonies not captured by sampling at 0.75 m, light limitation, the relative proportion of non-organic particulate vs. soluble P, shorter residence time, or a lack of nutrient limitation near the river mouth. However, the consistently positive relationship suggests that phosphorus concentration decreases should promote lower primary productivity (Stow and Cha 2013).

Western Lake Erie's algal biomass, since the late 1990s, has been correlated with

Maumee River spring phosphorus load (Stumpf et al. 2012, Obenour et al. 2014), which may seem to contrast our result of only modest relationships between phosphorus load and lake concentration. However, the algal biomass reported in these studies is an estimate for the entire western basin, which captures the spatial extent of the bloom, not necessarily local phytoplankton intensity. Higher spring loads result largely from higher river flow, which carries phosphorus farther into the lake where variable circulation patterns can widely distribute phosphorus resulting in a more spatially extensive bloom. Thus, when evaluating the effect of fluctuating loads it is important to differentiate the bloom spatial extent, which is strongly determined by Maumee River flow (Stumpf et al. 2012), from phytoplankton density, which is influenced by local phosphorus concentration.

These results have important implications for monitoring conducted to evaluate Lake Erie's response to management actions to meet the new load targets and for guiding public expectations. Higher loads will continue to cause spatially extensive blooms, but these result largely from annual differences in precipitation, temperature, and antecedent soil moisture, which are independent of phosphorus management activities. Thus evaluating yearly load changes over time may not clearly reflect phosphorus mitigation activities in the basin. Additionally, both precipitation (USGCRP 2018) and Maumee River flow have been increasing (Stow et al. 2015) which may obscure, or even partially offset, the effect of phosphorus management efforts. To separate these, Choquette et al. (2019) presented methods to track load changes by removing the effect of changing river flow. However, effective watershed management actions should eventually lower Maumee River phosphorus concentrations sufficiently to reduce western basin phosphorus and chlorophyll *a* concentrations. Assessing these responses in the lake requires a large-scale monitoring network to effectively document both changes in the spatial extent of the bloom and local phosphorus concentrations.

FIGURES

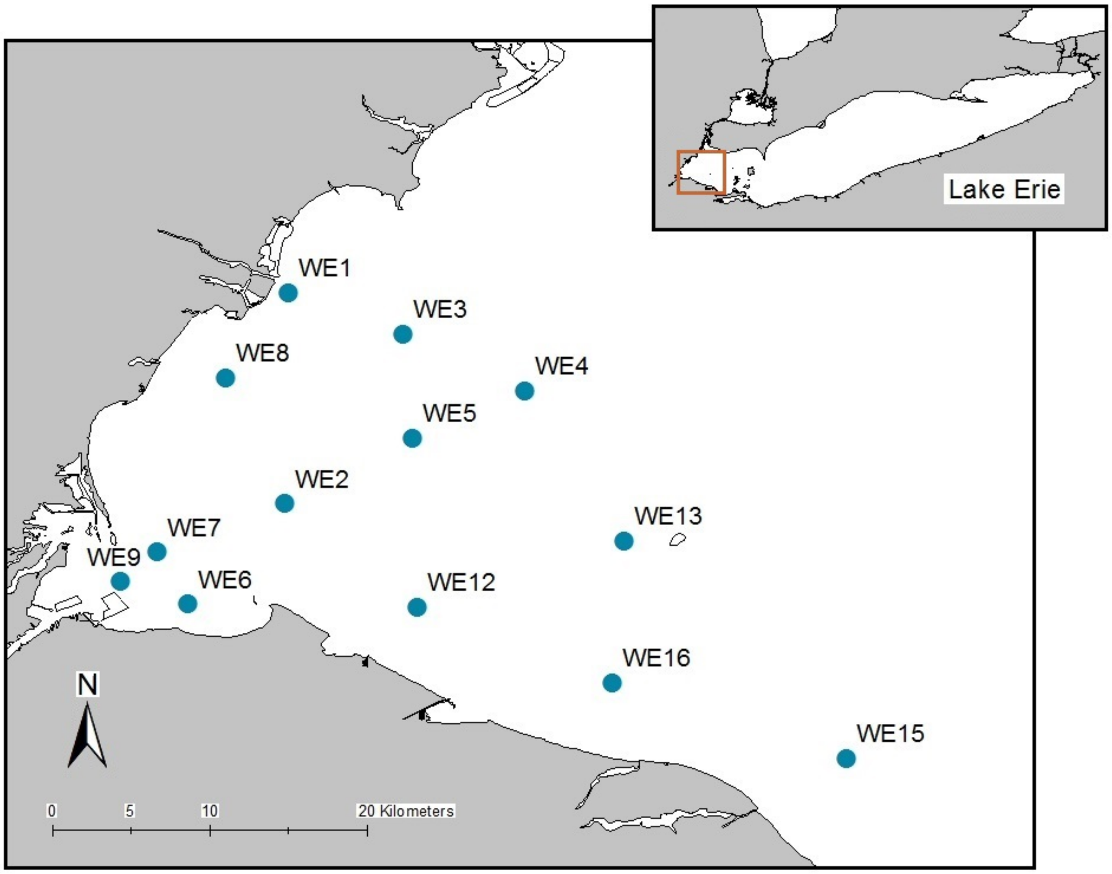

Figure 1. Regularly sampled monitoring stations in the western basin of Lake Erie 2008–2018.

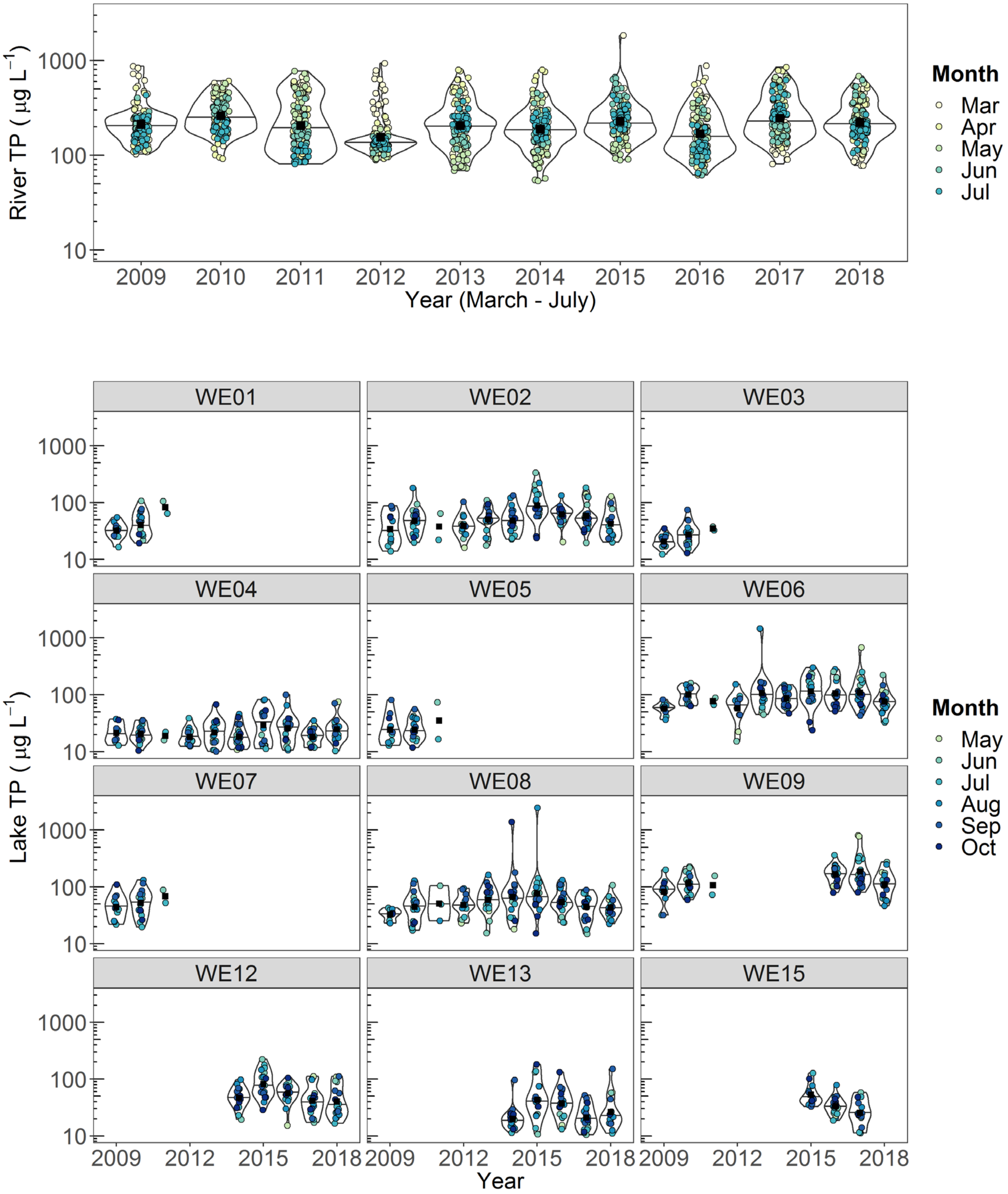

Figure 2. Total phosphorus (TP) in the Maumee River as daily flow-weighted mean concentrations (top panel) and lake concentrations at regularly monitored sites (bottom panel). Months are represented in different colors. For each violin, the horizontal line shows the median, and the black

squares show the average for a year. Only regularly sampled stations with more than one year of data are included.

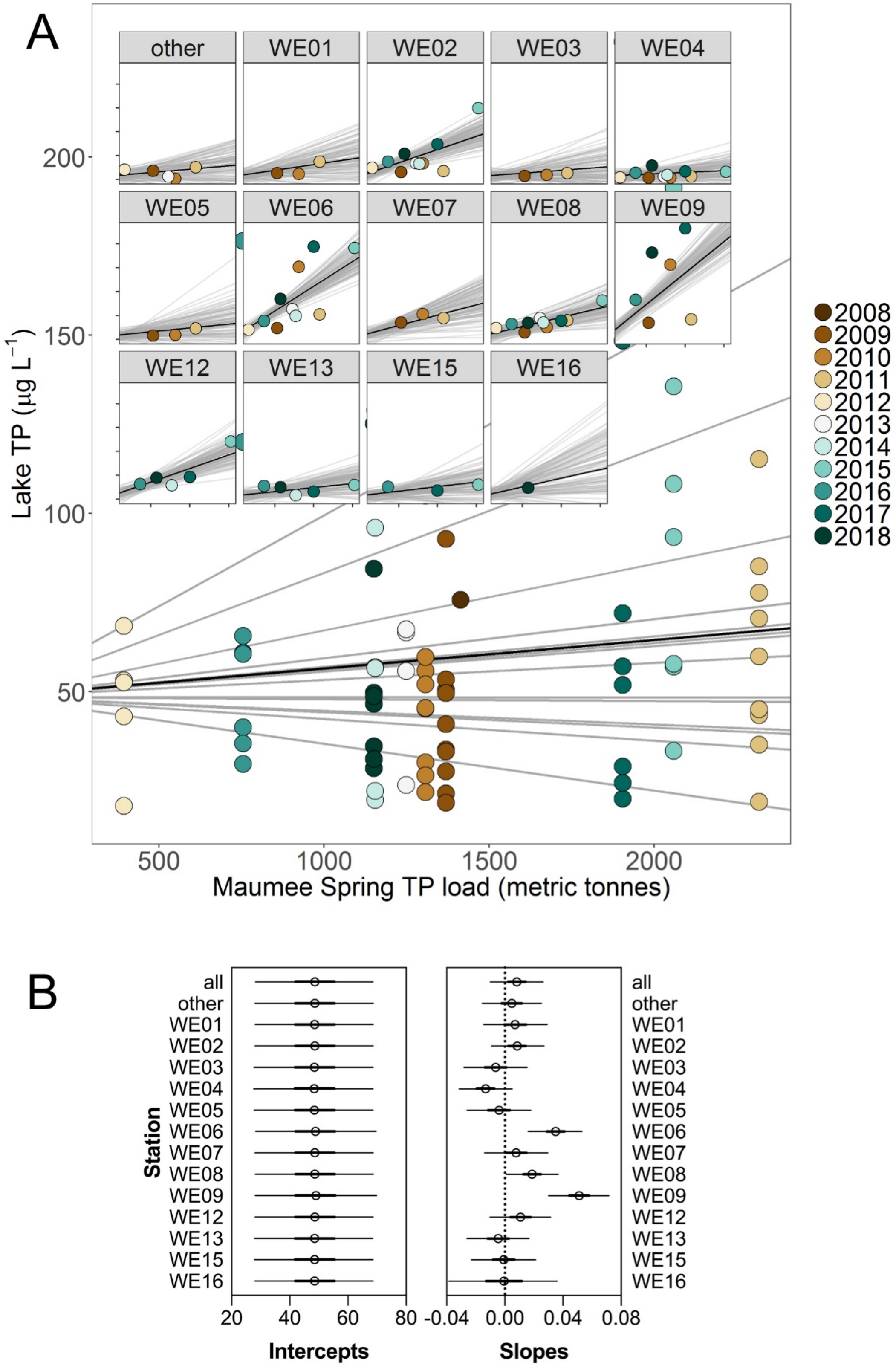
A
other
WE01
WE02
WE03
WE04
WE05
WE06
WE07
WE08
WE09
WE12
WE13
WE15
WE16
Lake TP (μg L^{-1})
200
150
100
50
500
1000
1500
2000
Maumee Spring TP load (metric tonnes)
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
B
Station
all
other
WE01
WE02
WE03
WE04
WE05
WE06
WE07
WE08
WE09
WE12
WE13
WE15
WE16
20
40
60
80
Intercepts
-0.04
0.00
0.04
0.08
Slopes

Figure 3. Maumee River spring (1 Mar–30 Jul) loads vs. lake concentrations for total phosphorus (TP) 2008–2018 in Lake Erie. (A) Regularly sampled sites (Figure 1) and extra samples (“other”) are depicted in inset with estimated regression plus 100 posterior draws (gray lines). The larger figure depicts the intercepts and slopes estimated for each station (gray lines) and overall regression (black line). Each point represents an average of all samples from a site within a year. (B) Coefficient means with 50% (thick line) and 95% (thin lines) credible intervals for the model.

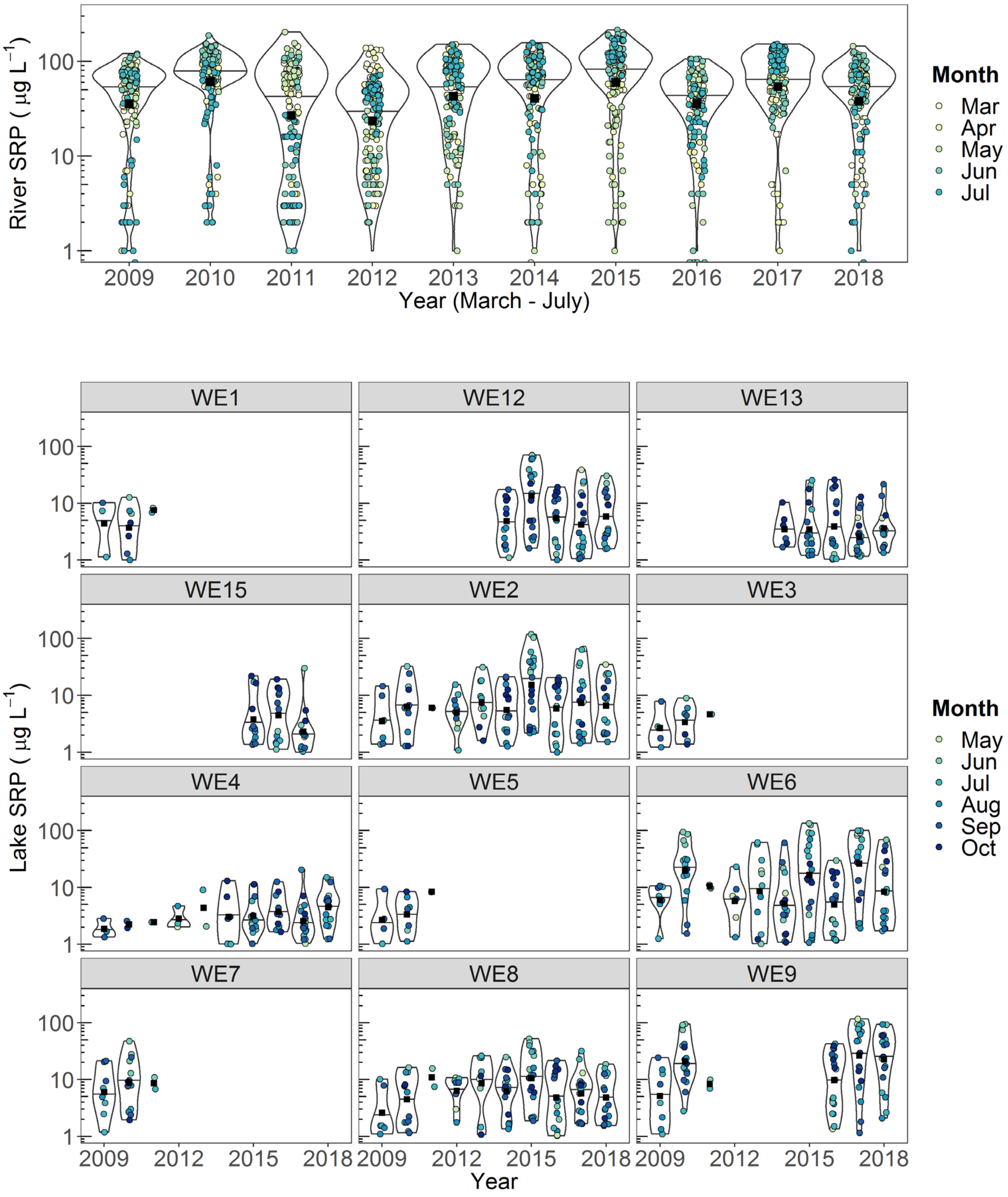

Figure 4. Soluble reactive phosphorus (SRP) in the Maumee River as daily flow-weighted mean concentrations (top panel) and lake concentrations at regularly monitored sites (bottom panel). Months are represented in different colors. For each violin, the horizontal line shows the median,

and the black squares show the average for a year. Only regularly sampled stations with more than one year of data are included.

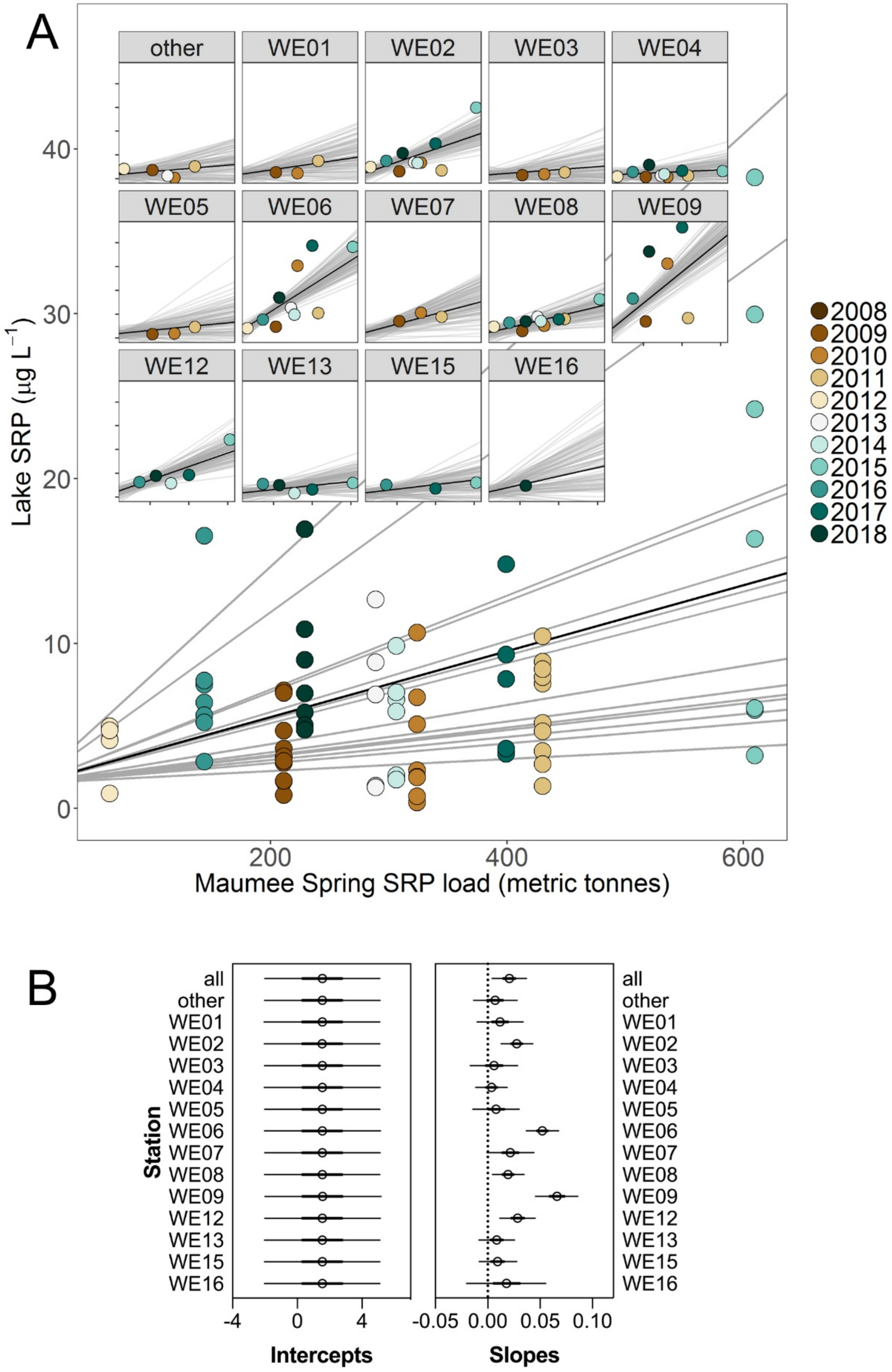
A
other
WE01
WE02
WE03
WE04
WE05
WE06
WE07
WE08
WE09
WE12
WE13
WE15
WE16
Lake SRP (μg L^{-1})
0
10
20
30
40
200
400
600
Maumee Spring SRP load (metric tonnes)
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
B
Station
all
other
WE01
WE02
WE03
WE04
WE05
WE06
WE07
WE08
WE09
WE12
WE13
WE15
WE16
-4
0
4
Intercepts
-0.05
0.00
0.05
0.10
Slopes

Figure 5. Maumee River spring (1 Mar–30 Jul) loads vs. lake concentrations for soluble reactive phosphorus (SRP) 2008–2018 in Lake Erie. (A) Regularly sampled sites (Figure 1) and extra samples (“other”) are depicted in inset with estimated regression plus 100 posterior draws (gray lines). The larger figure depicts the intercepts and slopes estimated for each station (gray lines) and overall regression (black line). Each point represents an average of all samples from a site within a year. (B) Coefficient means with 50% (thick line) and 95% (thin lines) credible intervals for the model.

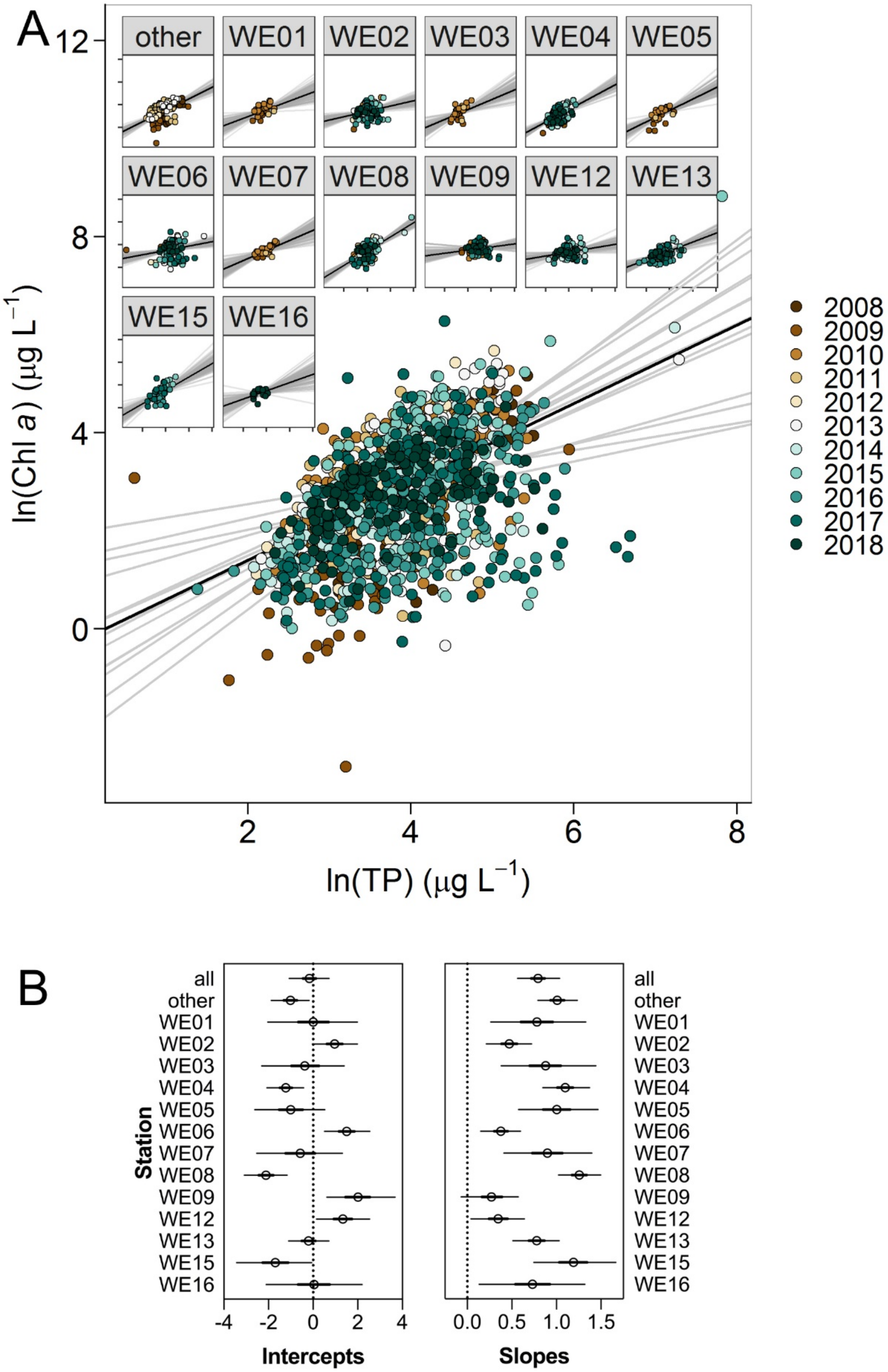
A
12
8
4
0
ln(Chl a) (μg L⁻¹)
2
4
6
8
ln(TP) (μg L⁻¹)
other
WE01
WE02
WE03
WE04
WE05
WE06
WE07
WE08
WE09
WE12
WE13
WE15
WE16
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
B
Station
all
other
WE01
WE02
WE03
WE04
WE05
WE06
WE07
WE08
WE09
WE12
WE13
WE15
WE16
-4
-2
0
2
4
Intercepts
0.0
0.5
1.0
1.5
Slopes

Figure 6. Chlorophyll *a* (chl *a*) vs. total phosphorus (TP) from 2008–2018 in Lake Erie. (A) Regularly sampled sites (Fig 1) and extra samples ("other") are depicted in inset with estimated regression plus 100 posterior draws. The larger figure depicts the intercept and slopes estimated for each station (gray lines) and overall regression (black line). (B) Coefficient means with 50% (thick line) and 95% (thin lines) credible intervals for the model.

TABLES.

Table 1. Site descriptions including years sampled, number of samples collected (n), and coordinates, and the average and range (min–max) of phosphorus and chlorophyll samples from the western basin of Lake Erie.

Site	Years	n[1]	Latitude	Longitude	Distance[2] from Maumee (km)	Total phosphorus (μg L^{-1})		Soluble reactive phosphorus (μg L^{-1})		Chlorophyll *a* (μg L^{-1})	
						avg	range	avg	range	avg	range
WE01	2009–2011	32	41.88265	-83.32794	24.0	44.2	(16.6–107.0)	2.9	(0.3–12.7)	27.7	(3.1–109.0)
WE02	2009–2018	167	41.76217	-83.33000	13.7	62.9	(13.9–334.0)	10.9	(0.04–118.0)	28.2	(0.7–194.0)
WE03	2009–2011	34	41.85920	-83.26237	25.0	27.4	(12.3–74.7)	1.9	(0.04–9.0)	22.0	(1.8–115.0)
WE04	2009–2018	164	41.82667	-83.19317	27.1	24.0	(5.9–99.7)	2.5	(0.04–20.6)	15.0	(0.4–120.0)
WE05	2009–2011	35	41.79967	-83.25732	21.0	28.1	(9.4–81.1)	2.0	(0.08–9.4)	14.4	(0.6–44.7)
WE06	2009–2018	166	41.70517	-83.38533	6.9	114.0	(1.8–1468.0)	19.7	(0.08–135.0)	49.4	(0.7–532.0)
WE07	2009–2011	34	41.73428	-83.40275	7.0	56.7	(19.8–132.0)	9.3	(0.4–47.6)	24.9	(5.4–99.3)
WE08	2009–2018	167	41.83400	-83.36383	17.8	80.5	(14.9–2482.0)	7.8	(0.1–52.6)	74.7	(0.8–6784.0)
WE09	2009–2018	93	41.71765	-83.42378	4.5	158.0	(31.8–807.0)	29.7	(0.4–117.0)	42.0	(4.4–183.0)
WE12	2014–2018	98	41.70317	-83.25433	17.7	63.6	(9.9–224.0)	11.1	(0.1–70.4)	22.1	(1.9–190.0)
WE13	2014–2018	94	41.74100	-83.13617	28.0	35.1	(4.0–182.0)	4.4	(0.05–26.1)	17.6	(1.6–173.0)
WE15	2015–2018	48	41.61667	-83.00933	39.1	39.4	(11.3–128.0)	4.9	(0.4–30.1)	30.5	(1.2–221.0)
WE16	2018	15	41.65968	-83.14287	27.3	31.1	(17.1–61.1)	4.8	(1.5–18.3)	14.4	(1.8– 26.9)
Other[3]	2008–2013	164	Various	Various	—	59.2	(10.4–380.0)	4.0	(0.03–20.9)	33.8	(0.1–180.0)

[1] All data are from surface samples collected at 0.75 m.

[2] The distance from the Maumee River was calculated as the straight line distance between the Maumee River mouth and each lake site.

[3] 'Other' includes sites that were sampled for only one season (n = 65) as well as opportunistic samples collected during algal blooms n = 99).

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ABBREVIATIONS

Chl *a*, chlorophyll *a*; CRI, credible interval; GLWQA, Great Lakes Water Quality Agreement; HAB, harmful algal bloom; SRP, soluble reactive phosphorus; TP, total phosphorus.

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