Revisiting phosphorus trends in the Western Lake Erie Basin

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# Abstract

Research Objective:

* Have the recent regulations and TMDL reduce P losses in the Western Lake Erie Basin
* We analyzed Blanchard, Honey, Maumee, Portage, Sandusky, and Tiffin within the basin and subject to Ohio laws
  + As references we used raisin (a watershed in the basin but located in Michigan)

# Introduction

# Methods and Materials

## Site Selection

To understand changing phosphorus trends in the basin, the weighted regression on time, discharge, and season (WRTDS) model within the EGRET package in R was used to characterize SRP and TP trends in 7 watersheds from 2008 to 2022 (Table 1). WY 2008 was chosen as the starting point because it has been previously set as the baseline year for phosphorus reduction targets in Lake Erie (Annex 4, 2015). The starting year varied at the Portage site due to a lack of data (Table 1). These sites were predominately chosen due to the availability of long-term data within the Nation Center for Water Quality Research (NCWQR) at Heidelberg University database (NCWQR, 2022). Remaining stations were excluded based on an insufficient period of water quality data, high percentage of urban or the potential for high flashiness (i.e., Richards-Baker Index), which would render them incompatible with the load estimation method used herein. These watersheds ranged from X to Y, and were predominately agricultural. Due to the highly agricultural nature of the watersheds, nutrient application is likely the core contributor of P (Kast et al., 2021).

At each site, we examined recent and long-term trends in soluble reactive phosphorus (SRP) and total phosphorus (TP) concentrations. The NCWQR has monitored nutrient concentrations in northwest Ohio by collecting and analyzing water quality samples near the nearby USGS stations using procedures and analytical methods described in (Baker et al., 2014). Over the periods of interest, anywhere from 300-500 samples were collected per year per site. In all cases, the annual percentage of days with missing concentration data was less than 15% (Supplemental Material, Table S1). Prior to analysis, we first aggregated sample concentrations into daily values by calculating the daily flow-weighted mean SRP and TP concentration on days when multiple measurements were available. Streamflow data from nearby were U.S. Geological Survey (USGS) gauging stations were downloaded from the USGS data portal using the R package *dataRetrieval*. All data were retrieved and analyzed by water year (WY), which is defined as the 12-month period from October 1 through September 30 and associated with the calendar year in which the WY ends.

Table 1: Site descriptions

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Watershed | Area (km2) | USGS Station ID | Data selected | | Agriculture (%) | Pasture (%) | Urban (%) | Subject to NM rules |
| Begin | End |
| Blanchard | 896 |  | 2008 | 2022 |  |  |  |  |
| Honey | 386 |  | 2008 | 2022 |  |  |  |  |
| Maumee | 16388 |  | 2008 | 2022 |  |  |  |  |
| Portage | 1108 |  | 2011 | 2022 |  |  |  |  |
| Raisin | 2698 |  | 2008 | 2022 |  |  |  | N |
| Sandusky | 3239 |  | 2008 | 2022 |  |  |  |  |
| Tiffin | 1061 |  | 2008 | 2022 |  |  |  |  |

## Analysis of Concentration and Flux trends

WRTDS estimates SRP and TP concentrations for every day of the period of record at each site using four components: the relation to discharge, seasonality, long-term trend, and a random component (Hirsch, Moyer, & Archfield, 2010; Sprague, Hirsch, & Aulenbach, 2011; Stackpoole, Sabo, Falcone, & Sprague, 2021). Estimates of daily concentration are multiplied by the respective daily mean streamflow to produce an estimate of the daily flux. Additionally, flow normalized (FN) concentrations and fluxes are also computed by WRTDS. Flow normalization aims to remove variations in concentration and flux caused by random variation in streamflow and has been found to provide the best available method for nutrient trend evaluation (Rowland, Stow, Johnson, & Hirsch, 2021; Sprague et al., 2011). The smoothing process that allows flow normalization to provide the best method for trend analysis, also means that flow normalization doesn’t provide the most accurate estimates of nutrient concentrations and loads. Therefore, an extension of WRTDS (WRTDS-Kalman, or WRTDS-K) was used to fill missing daily values and calculate daily estimates of the “actual” nutrient concentrations and loads. The FN values were used to assess trends in nutrient delivery across the sites. The “actual” concentrations and fluxes were used to identify extreme events and provide the reader with an idea of variability the actual annual flux values over the period.

Annual SRP and TP trends were estimated for the period from 2008 to 2022. Because the periods of interest were less than 20 years, streamflow was assumed to be stationary for all site (the windowSide argument for EGRET was set to 0). For the trend analyses, daily FN concentration and flux estimates were summarized into seasonal and annual means (for concentrations) and totals (for fluxes). From these annual means, the changes in FN values over the periods of interest were examined for each site and pollutant using the *runPairs* function in EGRET, which provides the net change in FN value between the start and end years and the net change in FN value as a percentage:

Net Change =

Net Change as a percentage =

where, is the annual FN concentration in year *t1*, is the annual FN concentration in year *t2*.

The uncertainty associated with annual FN trends was estimated using the EGRETci package (Hirsch, Archfield, & De Cicco, 2015). From this package, a bootstrap method supplied a likelihood statistic for all the estimated FN trends. This method provides 1) an indication of whether the null hypothesis, no trend over the period, should be rejected and 2) a measure of the estimated trend strength as described by a trend descriptor. For example, a trend (upward or downward) with a likelihood statistic between 0.95 and 1.0 would be described as “highly likely”, while a likelihood statistic of less than 0.05 would be described as “highly unlikely”. Further details on trend descriptors can be found in Hicks, Crain, and Segrest (2023).

In addition to the trends in annual FN values from 2008-2022, annual SRP and TP trends and their uncertainty were also estimated for the recent period from 2015-2022. Starting in 2015, the State of Ohio implemented regulations for fertilizer and manure application in the Western Lake Erie Basin (Section 905.326: Application of fertilizer in western basin. https://codes.ohio.gov/ohio-revised-code/section-905.326). Comparing the recent trends to the longer-term trends has the potential to elucidate the influence of these new regulations. Because WRTDS does not assume linearity of changes over time, rate of change can be compared between different parts of the record (Sprague et al., 2011). Seasonal trends were also estimated for both the longer-term and recent periods to identify when during the year that changes in water quality were occuring. For the seasonal analysis, the WY was split into 4 separate seasons: October – November (Fall), December – February (Winter), March – July (Spring), August – September (Summer; Fall). Spring was set for March 1 through July 31 because spring phosphorus loads have been found to correlate to the intensity of the HAB in the Western Lake Erie basin (Annex 4, 2015).

We used the rate of change in percent per year to compare FN trends across different periods:

Rate of change in percent per year =

where, *n* is *t2 – t1*. To examine changes in SRP and TP trends in recent years, we used the difference in the rate of change between the recent trend and the whole period (2015 to 2022 minus 2008 to 2022). Using this methodology, negative values indicated that there has been either a) a negative trend or b) a weaker positive trend in the past 7 years. While positive values indicated that there has been either a) a weaker negative trend or b) a positive trend in the past 7 years.

Model performance evaluations, including a visual assessment of the model fit and the detection of bias in residuals were completed, and deemed acceptable. All WRTDS models were run at the daily time step and the concentrations and loads were aggregated to seasonal or annual means. The annual FN and Kalman filter flux estimates were converted to common units (kg/km2). All analyses were conducted in the R statistical environment (R Core Team, 2022).

# Results & Discussion

## Annual changes in P in WLEB streams and rivers, 2008-2022

For the period from 2008 to 2022, examination of mean annual FN concentrations of SRP indicated that four of the seven sites had a highly likely upward trends with percent changes ranging from 33% at Sandusky to 128% at Blanchard (Table S1). The Maumee site had a slight upward trend with a percent change 0.5%, while the Tiffin and Honey sites each had likely downward trends with percent changes of -7 and -10%, respectively. For annual FN fluxes of SRP, four of the seven sites had very likely to highly likely upward trends with percent changes ranging from 12% at Portage to 33% at Blanchard (Table S2). The Honey and Tiffin sites had upward (1%) and downward (-7%) trends, but in both cases an upward trend was as likely as a downward trend. Only the Maumee site had a likely downward trend with a percent change of -6%. When examining TP trends from 2008 to 2022, mean annual FN concentrations of TP had likely or highly likely upward trends at all seven sites with percent changes ranging from 6% at the Maumee site to 48% at the Portage site (Table S3). Similarly, for annual FN TP fluxes, all seven of the sites had either very likely or highly likely upward trends. Across the seven sites, percent changes ranged from 10% at Maumee to 50% at Raisin (Table S4).

Overall, for the period between 2008-2022, percent changes were greatest at the Blanchard, Portage, Raisin, and Sandusky sites. The Blanchard site displaying the greatest percentage increases in FN SRP and TP concentrations, while the Sandusky site displayed the greatest percentage increase in FN SRP flux and the Raisin site displayed the greatest percentage increase in FN TP flux. Meanwhile, the Honey, Tiffin, and Maumee sites generally displayed near zero or negative percent changes for FN SRP and TP concentrations and fluxes. In general, the direction of FN SRP concentration and flux trends varied from site to site across the WLEB, while FN TP concentrations and fluxes increased at all sites.

Relative to P reduction targets in the WLEB, the downward trends in SRP fluxes in the Maumee River and the Tiffin River (a smaller tributary of the Maumee) indicate that some regional progress is being made towards mitigating SRP delivery. However, the consistently positive percent changes in TP concentrations and fluxes across the basin suggest that we should temper our happiness with the downward trends in SRP in select watersheds. Additionally, the substantial increasing SRP and TP trends for Blanchard, Portage, and Sandusky rivers indicate that recent changes occuring in these watersheds, especially Blanchard and Portage, are increasing and not decreasing P export within these watersheds.

## Influence of recent trends on long-term trends (2015-2022 vs. 2008-2022)

For SRP trends, more sites had negative trends (e.g., Maumee for FN concentration and Honey and Raisin for FN flux) (Table 2). The sites with negative trends over the entire period had greater negative trends (e.g., Honey and Tiffin for FN concentration and Maumee and Tiffin for FN flux). Generally, sites with positive FN trends in the recent period showed declining or steady state upward trends relative to the entire period (e.g., Blanchard, Portage, and Raisin for FN concentration and Blanchard and Sandusky for FN flux). Notably, the Sandusky showed an increasing upward trend in recent years for SRP concentration, while Portage showed an increasing upward trend in recent years for SRP flux. These results suggest that either a) nutrient reduction strategies enacted in recent years have had a mitigating effect on SRP losses within the basin, b) the cumulative nutrient reduction strategies implemented over the previous decades have reached a critical point and begun improving water quality, c) legacy sources are diminishing within the basin, d) all or some of the above. However, the differing results across the basin (especially, the increasing upward trends in Sandusky and Portage) indicate that these improvements have not been observed to the same extent across the basin.

Table 2: Rate of change in FN SRP concentration and flux between 2008 and 2022 and between 2015 and 2022, in percent per year.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Site | FN concentration | | FN flux | |
| 2008-2022 | 2015-2022 | 2008-2022 | 2015-2022 |
| BLA | 9.2 | 3.1 | 2.4 | 1.8 |
| HON | -0.7 | -0.8 | 0.1 | -0.5 |
| MAU | 0.0 | -0.8 | -0.4 | -0.9 |
| POR | 9.1 | 7.6 | 1.1 | 1.3 |
| RAI | 4.9 | 1.6 | 1.5 | -1.4 |
| SAN | 2.4 | 3.3 | 1.6 | 1.6 |
| TIF | -0.5 | -2.5 | -0.5 | -2.4 |
| Average | 3.5 | 1.6 | 0.8 | -0.1 |

For TP trends, only a single site (Tiffin) had switched from an upward to a downward trend and even then, this switch only occurred in the FN concentration trend (Table 3). Furthermore, only a few sites showed a decline in the magnitude of an upward trend in recent years (e.g., Blanchard, Portage, and Raisin for FN concentration and Raisin and Tiffin for FN flux). Generally, unlike SRP trends, sites with positive FN trends in the recent period showed increasing upward trends relative to the entire period (e.g., Honey, Maumee, Raisin, and Sandusky for FN concentration and Blanchard, Honey, Maumee, Portage, and Sandusky for FN flux). These results suggest that the annual TP delivery has been increasing throughout the basin.

Table 3: Rate of change in FN TP concentration and flux between 2008 and 2022 and between 2015 and 2022, in percent per year.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Site | FN concentration | | FN flux | |
| 2008-2022 | 2015-2022 | 2008-2022 | 2015-2022 |
| BLA | 4.5 | 2.7 | 1.4 | 2.3 |
| HON | 1.0 | 1.4 | 1.3 | 1.4 |
| MAU | 0.5 | 1.3 | 0.8 | 1.9 |
| POR | 4.4 | 4.1 | 2.0 | 2.3 |
| RAI | 2.8 | 1.4 | 3.6 | 2.1 |
| SAN | 1.7 | 4.0 | 2.3 | 3.9 |
| TIF | 0.5 | -0.7 | 1.5 | 0.6 |
| Average | 2.2 | 2.0 | 1.8 | 2.1 |

## Influence of flow conditions on P trends

### Sites with increasing trends in recent years

### Sites with decreasing trends in recent years

![A picture containing histogram

Description automatically generated]()

## Seasonal dynamics in P trends

### Fall (Oct-Nov) P dynamics in WLEB streams and rivers

The P fluxes released during the fall season encompassed 10 to 16% of the annual SRP FN flux and 8 to 12% of the annual TP flux (Table 4). From 2008-2022, trends in FN flux were upward at nearly every site for both SRP and TP (at Honey Creek, the fall SRP FN flux trend was slightly negative (-0.1 %/yr)). Upward trends were slightly greater for TP than SRP (Table 4). Relative to the whole period, fall SRP FN flux upwards trends in recent years (from 2015-2022) have either weakened or become downward trends at all sites except for Sandusky. This widespread weakening of upward trends or even switches to downward trends indicates that current management practices may be reducing SRP losses during the fall seasons. However, this is not the case for fall TP FN fluxes, where three of the sites showed increasing upward trends, one site saw no difference in its upward trend, and only three sites showed weakening upward trends or switches to downward trends. These trends indicate that fall TP losses have been increasing in the basin.

Table 4: Overview of SRP and TP FN fluxes during the fall season. The fall season lasted from 1 Oct through 31 Nov. FN flux trends are reported as the rate of percent change (%) over the period of interest. The percentage of annual FN Flux is the mean percentage of the FN flux released during the fall season from 2008-2022.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Sites | SRP | | | TP | | |
| Percentage of annual FN Flux | FN flux trends | | Percentage of annual FN Flux | FN flux trends | |
| 2008-2022 | 2015-2022 | 2008-2022 | 2015-2022 |
| BLA | 12 | 3.0 | 2.5 | 9 | 2.7 | 3.6 |
| HON | 16 | -0.1 | -0.1 | 10 | 2.0 | 2.9 |
| MAU | 10 | 1.5 | 0.7 | 8 | 1.5 | 1.5 |
| POR | 16 | 1.2 | 1.1 | 12 | 3.3 | 3.1 |
| RAI | 12 | 2.6 | 0.4 | 9 | 2.8 | -0.2 |
| SAN | 12 | 2.4 | 2.8 | 8 | 4.4 | 6.6 |
| TIF | 13 | 0.3 | -2.8 | 10 | 1.2 | -1.4 |
| Average | 13 | 1.6 | 0.7 | 9 | 2.6 | 2.3 |

### Winter (Dec-Feb) P dynamics in WLEB streams and rivers

The P fluxes released during the winter season ranged from 29 to 36% of the annual SRP FN flux and 29 to 33% of the annual TP flux (Table 5). These values make the winter the season with the second largest amount of P delivery to downstream waterbodies. From 2008-2022, winter SRP fluxes were downward at four sites, ranging from the small Honey Creek watershed to the larger Maumee watershed, and upward at Blanchard, Sandusky, and Raisin. Relative to the whole period, winter SRP FN flux trends in recent years (from 2015-2022) were either weaker upward, transitions to downward, or stronger downward trends at each site.

Unlike SRP trends, winter FN flux trends for TP were upward at all sites over the whole period (2008-2022) (Table 5). Although winter FN flux trends were upward across the whole period, only three of the sites showed increasing upward trends, one site saw no difference in its upward trend, and three sites showed weakening upward trends in recent years. While three sites with weakening upward trends shows some improvement in TP losses across the basin, the three sites with stronger upward trends included the two largest watersheds in the basin, Maumee and Sandusky. Overall, the winter FN trends for SRP and TP matched those of the fall season with the widespread weakening of upward trends, transitions to downward trends, and strengthening downward trends indicate that current management practices may be reducing SRP losses during the winter seasons, while the strengthening upward trends in winter TP fluxes in large watersheds suggest that winter TP losses have been increasing in the basin.

Table 5: Overview of SRP and TP FN fluxes during the winter season. The winter season lasted from 1 Dec through 28/29 Feb. FN flux trends are reported as the rate of percent change (%) over the period of interest. The percentage of annual FN Flux is the mean percentage of the FN flux released during the winter season from 2008-2022.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Sites | SRP | | | TP | | |
| Percentage of annual FN trend | FN flux trends | | Percentage of annual FN trend | FN flux trends | |
| 2008-2022 | 2015-2022 | 2008-2022 | 2015-2022 |
| BLA | 32 | 2.0 | 1.7 | 32 | 1.5 | 2.1 |
| HON | 34 | -0.2 | -0.8 | 33 | 0.8 | 0.1 |
| MAU | 35 | -0.5 | -1.4 | 33 | 0.7 | 1.4 |
| POR | 29 | -0.3 | -0.3 | 30 | 1.6 | 1.6 |
| RAI | 32 | 0.3 | -2.9 | 31 | 3.0 | 0.5 |
| SAN | 36 | 1.1 | 1.0 | 34 | 2.5 | 3.4 |
| TIF | 32 | -0.6 | -2.5 | 29 | 1.3 | 0.4 |
| Average | 33 | 0.3 | -0.7 | 32 | 1.6 | 1.4 |

### Spring (Mar-Jul) P dynamics in WLEB streams and rivers

The P fluxes released during the spring season ranged from 47 to 52% of the annual SRP FN flux and 54 to 58% of the annual TP flux (Table 6). Thus, the spring season delivers the largest relative amount of P within the year. Therefore, percent changes in the spring season represent the largest relative changes in P delivery and have the largest relative influence on annual P delivery. From 2008-2022, spring SRP fluxes were upward at five of the seven sites, with only Tiffin and Maumee sites showing downward trends. The greatest of these upward trends occurred at the Blanchard site. Relative to the whole period, spring SRP FN flux trends in recent years (from 2015-2022) were either weaker upward, transitions to downward, or stronger downward trends at every site except for Portage – where the upward trend had strengthened. These results suggest that efforts to reduce SRP export and improve water quality in the basin has been having a positive effect – if only a slight positive effect.

Again, unlike SRP trends, spring FN flux trends for TP were upward at all sites over the whole period (2008-2022) (Table 6). Furthermore, spring TP flux trends showed increasing upward trends at five sites in recent years. Only the Tiffin and Raisin sites didn’t show increasing upward trends, instead they showed weakening upward trends. The strengthening upward trends in spring TP fluxes in large watersheds suggest that - similar to the other season - spring TP losses have been increasing across the basin.

Table 6: Overview of SRP and TP FN fluxes during the spring season. The spring season lasted from 1 Mar through 31 Jul. FN flux trends are reported as the rate of percent change (%) over the period of interest. The percentage of annual FN Flux is the mean percentage of the FN flux released during the spring season from 2008-2022.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Sites | SRP | | | TP | | |
| Percentage of annual FN trend | FN flux trends | | Percentage of annual FN trend | FN flux trends | |
| 2008-2022 | 2015-2022 | 2008-2022 | 2015-2022 |
| BLA | 49 | 2.4 | 1.7 | 56 | 1.1 | 2.2 |
| HON | 47 | 0.4 | -0.5 | 54 | 1.5 | 1.8 |
| MAU | 52 | -0.7 | -1.0 | 57 | 0.7 | 2.2 |
| POR | 49 | 1.6 | 1.8 | 54 | 1.8 | 2.3 |
| RAI | 51 | 1.5 | -1.5 | 57 | 4.1 | 3.3 |
| SAN | 48 | 1.7 | 1.5 | 55 | 1.9 | 3.7 |
| TIF | 51 | -0.7 | -2.2 | 58 | 1.7 | 1.2 |
| Average | 50 | 0.9 | 0.0 | 56 | 1.8 | 2.4 |

### Summer/Fall (Aug-Nov) P dynamics in WLEB streams and rivers

The P fluxes released during the summer season ranged from 2 to 6% of the annual SRP FN flux and 1 to 3% of the annual TP flux (Table 7). Thus, the summer season encompasses the lowest P delivery from the WLEB. From 2008-2022, trends in FN flux were upward at every site for both SRP and TP. Furthermore, the percent changes during the summer season had the greatest magnitude of

Upward trends were slightly greater for TP than SRP (Table 4). Relative to the whole period, fall SRP FN flux upwards trends in recent years (from 2015-2022) have either weakened or become downward trends at all sites except for Sandusky. This widespread weakening of upward trends or even switches to downward trends indicates that current management practices may be reducing SRP losses during the fall seasons. However, this is not the case for fall TP FN fluxes, where three of the sites showed increasing upward trends, one site saw no difference in its upward trend, and only three sites showed weakening upward trends or switches to downward trends. These trends indicate that fall TP losses have been increasing in the basin.

Table 7: Overview of SRP and TP FN fluxes during the summer season. The summer season lasted from 1 Aug through 30 Sep. FN flux trends are reported as the rate of percent change (%) over the period of interest. The percentage of annual FN Flux is the mean percentage of the FN flux released during the summer season from 2008-2022.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Sites | SRP | | | TP | | |
| Percentage of annual FN trend | FN flux trends | | Percentage of annual FN trend | FN flux trends | |
| 2008-2022 | 2015-2022 | 2008-2022 | 2015-2022 |
| BLA | 6 | 4 | 1.8 | 3 | 2.8 | 3.2 |
| HON | 2 | 0.4 | 1.2 | 1 | 2.1 | 4.1 |
| MAU | 3 | 2 | 2.3 | 2 | 0.8 | 1.5 |
| POR | 6 | 6 | 5.2 | 3 | 4.5 | 4.2 |
| RAI | 5 | 9.8 | 5.4 | 3 | 3.2 | 2.1 |
| SAN | 3 | 4.3 | 5.4 | 2 | 3.6 | 6.7 |
| TIF | 3 | 0.2 | -2 | 2 | 0.2 | -1.7 |
| Average | 4 | 3.8 | 2.8 | 2 | 2.4 | 2.9 |

### Influential seasons on trend dynamics

For SRP, the winter season (Dec - Feb) trends were generally lower than the annual fluxes indicating that winter SRP losses either mediated upward annual trends or strengthened downward annual trends. Alternatively, the summer season (Aug-Sep) trends were generally greater than the annual trend, indicating that summer SRP losses have been increasing across the basin and may be a driving force some the upward annual SRP trends in the WLEB. Additionally, the fall season (Oct – Nov) was also generally greater than annual trends, especially at the Blanchard and Maumee sites. With the size of the Maumee watershed, this which indicated that these were also drivers of and spring (Mar – July) seasons

## Nutrient Application Rules

## Potential influence of watershed characteristics

### Blanchard

### Livestock populations in the counties

# Conclusion

# References

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