phosphorus concentration and load changes in the Western Lake Erie Basin under recent nutrient management regulations

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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, Sandusky, and Tiffin within the basin, which are subject to Ohio laws.
  + As references we used Raisin (a watershed in the basin but located in Michigan)

# Introduction

21st century residents of the Great Lakes region have witnessed the re-eutrophication of Lake Erie (Baker et al., 2014; Scavia et al., 2014). This re-eutrophication has been driven by increasing nonpoint source soluble reactive phosphorus (SRP) loads from major tributaries in the Western Lake Erie Basin (WLEB) like the Maumee and Sandusky Rivers (Baker et al., 2014; Jarvie et al., 2017; Michalak et al., 2013; Scavia et al., 2014). In tandem with this re-eutrophication, pervasive harmful and nuisance algal blooms (HNABs) have returned to Lake Erie, including massive HNABs in the summers of 2011 and 2015 and the microcystin containing HNAB in August of 2014 that led to 400,000 Ohio residents unable to drink or use their tap water (Smith et al., 2015).

To improve the water quality of Lake Erie, policymakers and scientists have recommended a reduction in phosphorus loading to the WLEB. For example, the Ohio Lake Erie Phosphorus Task Force recommended 37% and 41% reductions in the average spring loads (relative to a 2007-2012 baseline) of total phosphorus and SRP, respectively, to significantly reduce or eliminate HNABS (OhioTaskForce, 2013). Then in 2016, as part of the updated Great Lakes Water Quality Agreement, the United States and Canada adopted a target to reduce annual P loads to Lake Erie by 40% relative to the 2008 baseline load to reduce the extent of algal blooms in the basin (USEPA, 2016).

To meet these targets, states have developed nutrient reduction strategies that focus on implementing best management practices (BMPs) or agricultural conservation practices (ACPs) to reduce nutrient loss from agricultural fields. For example, the Ohio EPA updated the nonpoint source managment plan in 2014 (cite plan). Along with the updated management plan, the Ohio General Assembly enacted Senate Bill 1 in 2015 to address nutrient pollution in the WLEB (Section 905.326: Application of fertilizer in western basin. <https://codes.ohio.gov/ohio-revised-code/section-905.326>). This legislation included two core measures. First, no person can apply fertilizer or manure without a certification. Second, a person may not apply fertilizer or manure on snow-covered or frozen soil, saturated soil, or when the local weather forecast contains a greater than 50% chance of precipitation exceeding 0.5” in a 24-hour period unless the nutrient applied is subsequently incorporated into the soil. These regulations became effective on 3July 2015. Violations of these regulations can result in corrective action orders and civil penalties up to $10,000. To the authors knowledge, this is the first nutrient management regulation in the midwestern USA, which therefore prompts great interest in the effectiveness of the regulations to reduce phosphorus export.

Winter manure bans have the potential to be effective measures for P load reduction because nutrient applied to frozen or snow covered soils have a greater runoff risk (Liu et al., 2018; Prasad, Thompson, Arriaga, & Vadas, 2022; Srinivasan, Bryant, Callahan, & Weld, 2006; Stock et al., 2019). Furthermore, the restriction of application in the 24 hours before a precipitation event follows the results of Smith, Owens, Leytem, and Warnemuende (2007), which found that the greatest risk of P loss occurred when rainfall occurred 1 day after fertilization and dropped drastically if precipitation occurred after that. Finally, the exception for incorporation should not void or reduce the effectiveness of the regulation because subsurface application has been shown to reduce SRP losses from agricultural fields (Kamrath & Yuan, 2023; King et al., 2018). From these studies, we hypothesized that the nutrient management rules will reduce P losses from agricultural watersheds in the WLEB, especially during the winter season.

Here we focused the Maumee River watersheds, one of the largest contributors of P to the WLEB (Stumpf, Wynne, Baker, & Fahnenstiel, 2012). To quantify SRP and total phosphorus (TP) trends, we used the flow-normalized (FN) concentrations and fluxes derived from the weighted regression on time, discharge, and season (WRTDS) model (Choquette, Hirsch, Murphy, Johnson, & Confesor, 2019; Hirsch, Moyer, & Archfield, 2010). 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, Hirsch, & Aulenbach, 2011). Overall, this study can be portioned into 3 distinct objectives: 1) investigate recent trends for changes in response to nutrient management rules and regulations, 2) contextualize changes in P trends with respect to flow conditions and season to elucidate potential causes for trends, and 3) assess the annual P trends across the basin since 2009.

# Methods and Materials

## Site Selection

To understand changing phosphorus trends in the basin, the WRTDS model was used to characterize SRP and TP trends in 6 watersheds within the WLEB from 2009 to 2021 (Table 1). These sites were predominately chosen due to the availability of long-term data within the National 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., high Richards-Baker Index), which would render them incompatible with the WRTDS model used herein. These watersheds ranged from 386 to 16388 km2 and were predominately agricultural (Table 1). 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 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 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. 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 (%) | Urban (%) | Subject to NM rules |
| Begin | End |
| Blanchard | 896 | 04193500 | 2008 | 2022 | 79 | 10 | Y |
| Honey | 386 | 04185000 | 2008 | 2022 | 81 | 7 | Y |
| Maumee | 16388 | 04189000 | 2008 | 2022 | 73 | 11 | Y |
| Raisin | 2698 | 04198000 | 2008 | 2022 | 50 | 11 | N |
| Sandusky | 3239 | 04197100 | 2008 | 2022 | 78 | 8 | Y |
| Tiffin | 1061 | 04176500 | 2008 | 2022 | 60 | 8 | Y |

## Analysis of Concentration and Flux trends

Weighted regressions on time, discharge, and season (WRTDS) was designed to extract the maximum amount of information from water quality datasets, such as those collected by National Water Quality Research Laboratory (Hirsch et al., 2010). It is a diagnostic tool useful to identify water quality changes occuring in a watershed related to nonpoint sources pollution over a period. Thus, the WRTDS was used to estimate SRP and TP concentration and flux changes over time (2008-2022). The key of this method is that it was designed to provide internally consistent estimates of the actual history of concentrations and fluxes that eliminate the influence of year-to-year variations in streamflow. Results produced from this method are useful in further examination of the causes of changes, or lack of changes, and may help inform decisions about future actions to reduce nonpoint source pollution.

Because the periods of interest were less than 20 years (2008-2022), streamflow was assumed to be stationary for all sites (the windowSide argument for EGRET was set to 0). Estimates of daily concentration are multiplied by the respective daily mean streamflow to produce an estimate of the daily flux (load). Using these estimates, flow normalized (FN) concentrations and fluxes were computed using the EGRET R package. FN fluxes were used for trend analysis. 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 “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 2009 to 2021. For the trend analyses, 2009 was chosen as the starting point because it provided a one-year buffer from the starting date at which data was available at all sites (Table 1). This buffer was necessary because WRTDS is a weighted regression on time and end point years can be influenced by past or future data. For the same reason, trends were established up to 2021. The use of 2009 as a starting point also puts the starting point of the analysis near the previously set as the baseline year of 2008 for phosphorus reduction targets in Lake Erie (Annex 4, 2015).

Daily FN flux estimates were summarized into seasonal and annual fluxes. From these values, 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 2009-2021, annual SRP and TP trends in fluxes were also estimated for the periods of 2009-2015 and 2015-2022 and then compared. Comparing these periods has the potential to elucidate the influence of nutrient reduction strategies, especially the 2015 nutrient management 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 the two short-term 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).

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, 2009-2021

Since 2009, three of the seven sites had a highly likely upward trends in mean annual FN concentrations of SRP with percent changes ranging from 27% at Sandusky to 103% at Blanchard (Table 2, Figure 1). The Maumee site had a slight negative trend with a percent change 0.5%, while the Tiffin and Honey sites each had likely downward trends with percent changes of -5 and -9%, respectively. For annual FN fluxes of SRP, three of the seven sites had very likely to highly likely upward trends with percent changes ranging from 19% at Sandusky to 28% at Blanchard (Table 2). The Honey and Tiffin sites had upward (2%) and downward (-5%) 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 -5%.

Table 2: SRP trends from 2009 to 2021.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Site | FN Concentration of SRP | | | FN Flux of SRP | | | |
| Annual mean in 2009, mg/L | Change, 2009 - 2021 | | Total annual flux in 2009, metric ton/yr | Total annual yield in 2009, kg/km2/yr | Change, 2009-2021 | |
| mg/L | % | Metric ton | % |
| Maumee | 0.07 | <0.005 | -0.4 | 602 | 36.7 | -30 | -5 |
| Tiffin | 0.05 | <0.005 | -5 | 25.4 | 23.9 | -1 | -5 |
| Blanchard | 0.12 | 0.12 | 103 | 38.7 | 43.2 | 11 | 28 |
| Sandusky | 0.05 | 0.01 | 27 | 124 | 38.3 | 23 | 19 |
| Honey | 0.08 | -0.01 | -9 | 21.3 | 55.2 | 1 | 2 |
| Raisin | 0.02 | 0.01 | 60 | 29.8 | 11.0 | 6 | 21 |

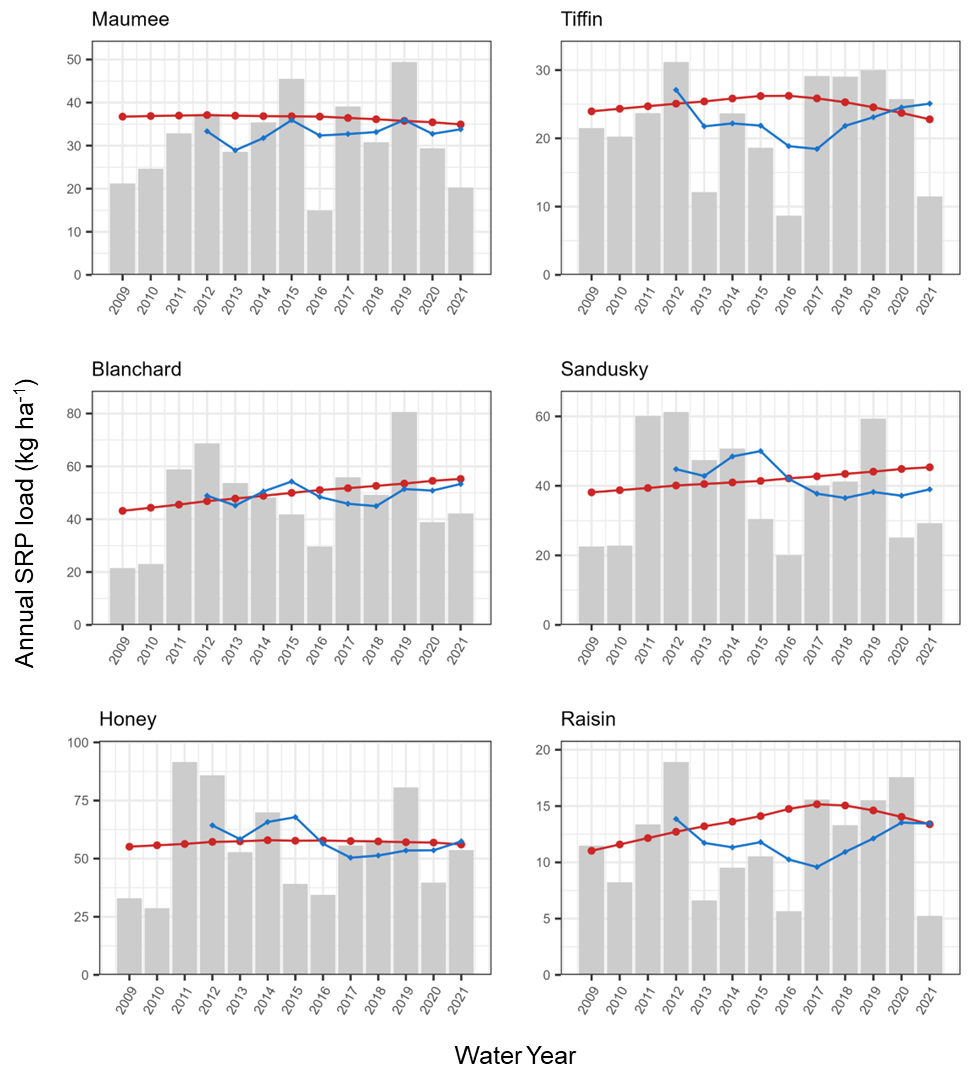


Figure 1: Annual SRP load (kg/km2) for the entire period of interest (2009-2021) across all sites. The gray bars in panels are the WRTDS Kalman Filter results. Red line shows the WRTDS flow normalized results. The Blue line shows the 5 year moving average of “actual” annual SRP loads.

When examining TP trends, 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 52% at the Blanchard site (Table 3, Figure 2). 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 9% at Maumee to 36% at Raisin (Table 3 & S4).

Table 3: TP trends from 2009 to 2021.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Site | FN Concentration of TP | | | FN Flux of TP | | | |
| Annual mean in 2009, mg/L | Change, 2009 - 2021 | | Total annual flux in 2009, metric ton/yr | Total annual yield in 2009, kg/km2/yr | Change, 2009-2021 | |
| mg/L | % | Metric ton | % |
| Maumee | 0.23 | 0.01 | 6 | 2390 | 145 | 300 | 9 |
| Tiffin | 0.16 | 0.01 | 6 | 82.4 | 78 | 16 | 16 |
| Blanchard | 0.25 | 0.13 | 52 | 137 | 153 | 32 | 18 |
| Sandusky | 0.20 | 0.04 | 21 | 530 | 164 | 205 | 29 |
| Honey | 0.20 | 0.02 | 12 | 68.6 | 178 | 10 | 11 |
| Raisin | 0.08 | 0.03 | 34 | 113 | 42 | 50 | 36 |



Figure 2: Annual TP load (kg/km2) for the entire period of interest (2009-2021) across all sites. The gray bars in panels are the WRTDS Kalman Filter results. Red line shows the WRTDS flow normalized results. The Blue line shows the 5 year moving average of “actual” annual SRP loads.

Overall, for the period between 2009 and 2021, percent changes in phosphorus were greatest at the Blanchard, 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 was mixed from site to site across the WLEB, while FN TP concentrations and fluxes increased at all sites.

Although, flow-normalization reduces the noise associated with trends, concentrations trends still tend to be biased toward low flow observations (due to the greater number of low flow observations), while flux trends are biased toward high flow observations (Sprague et al., 2011). Thus, the greater increase in SRP and TP concentrations at Blanchard suggests that the baseflow or low flow concentrations are increasing at a greater magnitude than the high flow concentrations. Sites within increasing SRP trends generally had greater increases in SRP concentrations than SRP fluxes, while sites generally had a greater increase in flux than concentration for TP. This would suggest that in the WLEB, where SRP is increasing, it is generally increasing more at low flow, but TP is generally increasing more at high flows.

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 hopes that the downward trends in SRP in select watersheds are harbingers of broad reductions in P delivery to Lake Erie. Additionally, the substantial increasing SRP and TP trends for Blanchard and Sandusky rivers indicate that recent changes occuring in these watersheds, especially Blanchard, are increasing and not decreasing P export within these watersheds. Interestingly, the Tiffin and Blanchard watersheds are both of similar size and located within the overall Maumee River watersheds. Future research could be instituted to determine why the Tiffin site is experiencing progress towards reduced P delivery, while the Blanchard site is not only lacking progress, but actively exporting more P since 2009.

## Influence of recent trends (2009-2015 vs. 2015-2021)

For SRP, FN concentration percent changes were lower since 2015 for all sites, except Sandusky (Table 4). In recent years, two sites had lower positive trends, two sites flipped from a positive to a negative trend, and one site had a greater negative trend. For FN flux, a similar overall trend of lower rates of change since 2015 was observed. Here, one site had a lower positive value in recent years, while four sites flipped from a positive to a negative value. Again, the Sandusky site was the exception, with a greater positive value in FN flux in recent years. The average percent change across the six sites reflects the site by sites observations with a reduction in FN concentration values from 22 to 4 % and a reduction in FN flux from 11 to -1 %.

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) indicate that these improvements have not been observed to the same extent across the basin. Furthermore, these trends are subject to uncertainty and the relatively small percent changes have the potential to offset by estimation errors.

Table 4: Rate of change in FN SRP concentration and flux between 2009 and 2015 and between 2015 and 2021, in percent.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Site | FN concentration | | FN flux | |
| 2009-2015 | 2015-2021 | 2009-2015 | 2015-2021 |
| Maumee | 5 | -5 | 0 | -5 |
| Tiffin | 10 | -14 | 9 | -13 |
| Blanchard | 70 | 19 | 16 | 11 |
| Sandusky | 7 | 19 | 9 | 9 |
| Honey | -4 | -5 | 5 | -3 |
| Raisin | 43 | 12 | 28 | -5 |
| Average | 22 | 4 | 11 | -1 |

For TP, two sites had lower positive rates of changes in recent years and one site flipped from a positive to a negative trend; meanwhile, two sites flipped from a negative to a positive trend and one site had an increased positive trend (Table 5). For FN flux, a similar overall trend to FN concentration was observed. Two sites had lower positive trends in recent years; however, one site flipped from a negative to a positive trend and three sites had an increased positive trend in recent years. The average changes across the six sites reflect the site by sites observations with stable FN concentration change of 10 % in both periods and a slight decrease in FN flux values from 11 to 7 %. Generally, unlike SRP trends, sites with positive FN values in the recent period showed increasing upward trends since 2015. These results suggest that the annual TP delivery has been increasing throughout the basin.

Table 5: Rate of change in FN TP concentration and flux between 2009 and 2015 and between 2015 and 2021, in percent per year.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Site | FN concentration | | FN flux | |
| 2009-2015 | 2015-2021 | 2009-2015 | 2015-2021 |
| Maumee | -2 | 7 | 1 | 8 |
| Tiffin | 10 | -4 | 12 | 3 |
| Blanchard | 31 | 16 | 5 | 12 |
| Sandusky | -2 | 23 | 8 | 19 |
| Honey | 3 | 8 | 10 | 0 |
| Raisin | 23 | 9 | 31 | 3 |
| Average | 10 | 10 | 11 | 7 |

## Seasonal dynamics in P trends

### 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 34% of the annual TP flux (Table 6). These values make the winter the season with the second largest amount of P delivery to downstream waterbodies. At five of the six sites, the percent changes in SRP winter fluxes were lower for the period after 2015 (Table 6). Furthermore, at four of these five sites, the percent changes in SRP fluxes were negative since 2015. The one exception site was Sandusky, which had a 6% change in FN SRP fluxes in both periods. Unlike SRP, the relationship between percent changes in TP FN fluxes for the two periods were variable. Three sites showed a decrease in the rate of TP fluxes, meanwhile three sites showed an increase (Table 6). Additionally, no sites showed a reduction in TP flux in either period. Furthermore, the two largest sites, Maumee and Sandusky, both showed increasing FN TP fluxes.

Overall, the winter FN trends for SRP showed widespread weakening of upward trends and transitions to downward trends, which indicate that current management practices may be reducing SRP losses during the winter seasons. Meanwhile, the strengthening upward trends in winter TP fluxes in large watersheds suggest that winter TP losses have been increasing in the basin since 2015.

Table 6: 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 | |
| 2009-2015 | 2015-2021 | 2009-2015 | 2015-2021 |
| Maumee | 35 | 2 | -8 | 33 | 1 | 8 |
| Tiffin | 32 | 9 | -14 | 29 | 12 | 4 |
| Blanchard | 32 | 12 | 10 | 32 | 5 | 12 |
| Sandusky | 36 | 6 | 6 | 34 | 8 | 19 |
| Honey | 34 | 3 | -5 | 33 | 10 | 0 |
| Raisin | 32 | 24 | -14 | 31 | 31 | 3 |
| Average | 34 | 9 | -4 | 32 | 11 | 8 |

### 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 2009 to 2015, spring SRP FN fluxes were upward at five of the six sites, with only Maumee showing a downward trend. The greatest of these upward trends occurred at the Raisin site (29%). From 2015 to 2022, spring SRP FN flux trends were either weaker upward, transitioned to downward, or stronger downward trends at every site. 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.

From 2009 to 2015, spring TP FN flux trends were generally positive or near zero, with only Maumee having a negative trend (Table 7). Unlike SRP trends, from 2015 to 2021 TP trends were generally stronger positive trends, indicating increasing TP export. Notable exceptions were Tiffin and Raisin, which had slightly weaker positive trends. TP trends at each site were positive at all sites in the recent period (2015-2021). The strengthening upward trends in spring TP fluxes in large watersheds suggest that spring TP losses have been increasing across the basin.

Table 7: 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 | |
| 2009-2015 | 2015-2021 | 2009-2015 | 2015-2021 |
| Maumee | 52 | -3 | -6 | 57 | -4 | 13 |
| Tiffin | 51 | 6 | -12 | 58 | 12 | 8 |
| Blanchard | 49 | 16 | 10 | 56 | 0 | 12 |
| Sandusky | 48 | 10 | 9 | 55 | 0 | 21 |
| Honey | 47 | 8 | -3 | 54 | 7 | 10 |
| Raisin | 51 | 29 | -6 | 57 | 23 | 21 |
| Average | 50 | 11 | -1 | 56 | 6 | 14 |

### Offseason (Aug-Nov) P dynamics in WLEB streams and rivers

The P fluxes released during the offseason ranged from12 to 17% of the annual SRP FN flux and 9 to 12% of the annual TP FN 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 8: 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 | |
| 2009-2015 | 2015-2021 | 2009-2015 | 2015-2021 |
| Maumee | 12 | 14 | 4 | 9 | 11 | 6 |
| Tiffin | 15 | 23 | -20 | 12 | 22 | -12 |
| Blanchard | 17 | 23 | 12 | 11 | 12 | 20 |
| Sandusky | 14 | 12 | 19 | 10 | 12 | 38 |
| Honey | 17 | -1 | 1 | 11 | 7 | 18 |
| Raisin | 17 | 39 | 4 | 11 | 33 | -2 |
| Average | 15 | 18 | 3 | 11 | 16 | 11 |

### 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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