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

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# Abstract

In 2015, the state of Ohio passed and enacted Senate Bill 1, which restricted the application of nutrients on frozen, snow-covered, saturated, or soon-to-be saturated soils. Here, we sought to understand and quantify the effectiveness of this regulation to reduce phosphorus export in the Western Lake Erie Basin (WLEB), as well as estimate the P export trends in the basin since 2008. To determine the effectiveness of the regulations, we compared seasonal flow-weighted mean concentrations of soluble reactive phosphorus (SRP), total phosphorus (TP), and total suspended solids (TSS) before (2008-2015) and after (2015-2022) the nutrient management regulations were implemented. For comparison, we obtained data from the Maumee River and two sub-watersheds of the Maumee River – the Tiffin and Blanchard Rivers. All of which were subject to Ohio laws. In addition to these sites, the River Raisin was selected as a reference site because it is located within the WLEB, but located in Michigan - outside the jurisdiction of the Ohio laws. We found that the regulations did reduce nutrient export during periods of enforcement with SRP and TP concentrations in the Maumee River decreasing by 20 and 17%, respectively, when soils were frozen and 10 and 10%, respectively, when the soils were thawing after the implementation of the nutrient management regulations. Additionally, the River Raisin either experienced increases in SRP and TP or smaller reductions during these frozen and thaw seasons, which furthered showed the potential for nutrient management regulations to reduce P export. However, our results also showed either increases or minor decreases in annual SRP, TP, and TSS fluxes in the Maumee River watershed - likely due to increases in SRP, TP, and TSS concentrations during the fall season. Furthermore, there was heterogeneity within the Maumee River watershed with the Blanchard River showing signs of worsening P export, while the Tiffin River showed signs of reduced P export. These results indicated that the nutrient management regulations may be shifting the timing of application but not the magnitude of the losses or that the change in timing is reducing the magnitude of P loss, but that the amount of P applied is increasing as animal populations in the watershed increased. This study showed that nutrient management regulations can have a positive impact on nutrient reduction during certain periods, but that this practice alone will not be a silver bullet by which the nutrient reduction targets in the WLEB are met.

# 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 concurrence 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. Specifically, the United States and Canada revised the Great Lakes Water Quality Agreement (GLWQA) and adopted targets to reduce P loading to Lake Erie. In this agreement, a target of a 40% reduction in both SRP and TP loads relative to the 2008 baseline load was set to reduce the extent of algal blooms in the basin (USEPA, 2016). Additionally, the SRP and TP loads from the Maumee River during the spring period (March through July) were found to be closely correlated with the severity of algal blooms in the WLEB (Annex 4, 2015; Baker et al., 2014). Therefore, the GLWQA also adopted a 40% reduction target for spring SRP and TP loads from the Maumee River (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. Along with the nutrient reduction strategies, 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 (Jacquemin, Johnson, Dirksen, & McGlinch, 2018; 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 regulations would reduce P losses from agricultural watersheds in the WLEB, especially during periods of frozen or thawing soils (i.e., winter and early spring), and help us progress towards the nutrient reduction targets for the WLEB.

To test our hypothesis, we quantified the effectiveness of the nutrient management regulations by assessing changes in seasonal and annual SRP, TP, and total suspended solids (TSS) delivery pre and post-nutrient management regulations in the Maumee River watershed, one of the largest contributors of P to the WLEB (Stumpf, Wynne, Baker, & Fahnenstiel, 2012). Because our study was conducted at the watershed scale, we did not attempt to parse out the effectiveness of individual practices. To assess the influence of the nutrient management regulations on the progress made towards the P reduction goals, we quantified annual and spring SRP and total phosphorus (TP) trends using annual flow-normalized (FN) concentrations and fluxes derived from the weighted regression on time, discharge, and season (WRTDS) model (Choquette, Hirsch, Murphy, Johnson, & Confesor, 2019; R. M. 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 was divided into three distinct objectives: 1) investigate SRP, TP, and TSS concentration changes during frozen soil, thawing soil, spring application, and fall application periods, 2) assess the annual FN P trends across the basin since 2008, and 3) compare recent FN P trends (2015 to 2022) to previous P trends (2008-2015).

# Methods and Materials

## Site Selection

SRP, TP, and TSS trends were evaluated in 4 watersheds within the WLEB from 2008 to 2022 (Table 1). The sites included the Maumee River, two sub-watersheds within the Maumee River (Tiffin and Blanchard), and the River Raisin. The River Raisin, while within the WLEB, is located in the state of Michigan and not subject to the State of Ohio’s nutrient management regulations. Therefore, the River Raisin acted as a general reference watershed in this study. Overall, these four watersheds ranged from 896 to 16388 km2. The Blanchard and Tiffin River watersheds account for approximately 5 and 6% of the entire Maumee River watershed, respectively. All four watersheds were predominately agricultural; therefore, nutrient application was likely the core contributor of P in each watershed (Kast et al., 2021).

Table 1: Site descriptions

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Watershed | Area (km2) | USGS Station ID | Data selected | | Agriculture (%) | Urban (%) | Subject to NM rules |
| Begin | End |
| Tiffin | 1061 | 04176500 | 2008 | 2022 | 60 | 8 | Y |
| Blanchard | 896 | 04193500 | 2008 | 2022 | 79 | 10 | Y |
| Maumee | 16388 | 04189000 | 2008 | 2022 | 73 | 11 | Y |
| Raisin | 2698 | 04198000 | 2008 | 2022 | 50 | 11 | N |

The National Center of Water Quality Research (NCWQR) has monitored nutrient concentrations in the WLEB since the 1970s. The Maumee and the Raisin sites had data going back to the 20th century, but sampling only began at the Tiffin and Blanchard sites in 2007. The NCWQR collected and analyzed water quality samples obtained near the USGS stations using methods described in Baker et al. (2014). The NCWQR analyzed 1 to 3 samples per day, depending on flow conditions, which resulted in 300 to 500 samples per year per site. Sub-daily sample concentrations were aggregated into daily values by calculating the daily flow-weighted mean concentration on days when multiple measurements were available. Streamflow data from nearby U.S. Geological Survey (USGS) gauging stations were downloaded from the USGS data portal using the R package *dataRetrieval* (DeCicco, Hirsch, Lorenz, Watkins, & Johnson, 2023). 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.

## Identifying Frozen Soil and Thaw Transition Periods

Using methods similar to Jacquemin et al. (2018), we sought to evaluate changes in nutrient export caused by or at least correlated with a manure application ban by comparing daily flow weighted mean concentrations (fwmc) pre- and post-regulation implementation both during and outside of the ban period. However, unlike the Grand Lake St. Mary's watershed in Jacquemin et al. (2018), a definitive period of no application was not prescribed as part of the WLEB nutrient application rules. Instead, the ruling states that fertilizer or manure cannot be applied on frozen or snow-covered soils. The problem with this terminology is threefold. First, snow cover can vary across the basin potentially causing spatial variability in application bans across watersheds in the WLEB. Second, and perhaps more importantly, there is interannual variation in the periods of snow-covered or frozen soils. For example, one December may have frozen soils for the entire month, while another December may have unfrozen soils for the entire month. In this case, a comparison of concentrations between Decembers may not elucidate the effects of nutrient application restrictions. Finally, the response of the treatment (i.e., nutrient or sediment concentration in stream discharge) has the potential to be delayed and occur when snow melts and soil thaws.

To adjust for these conditions and conduct a pre/post analysis based on specific time frames, we needed to define periods during which soils are most likely to be either frozen, thawing, or unfrozen. Soil frost-in and frost-out dates were derived from frost depth measurements recorded at the Ohio State University Northwest Agricultural Research Station in Wood County, Ohio. The station records average daily soil temperatures at 5 and 10 cm below the surface. Frozen surface soils were estimated to be present when the average daily soil temperature at 5 cm below the surface was below 34 degrees. We defined frost-in as the first date with frozen soils for seven consecutive days. The frost-in date was retroactively set to the first day of the seven consecutive days. To end the frost period, the soils needed to be unfrozen for 14 consecutive days. The frost-out date was retroactively set to the last day with frozen soils. Days between frost-in and frost-out were considered frozen soil days. The last day of frozen soil was set as day 0 for the thaw period. The thaw periods were determined by plotting the days before (as negative values) and after (as positive values) frost-out with respect to daily Q values. The period with greater Q values were determined to be thaw periods. This was conservatively identified as the period from 5 days before frost-out to 20 days after frost-out. These days were set as thaw days, with the 5 days before frost-out converted from frozen to thaw days. Any days without frozen soils or thawing soils was designated as a warm period day. The warm period was split into either a spring (before July 1st) or fall (after and including July 1st) application period.

## Data Analysis

Changes in SRP, TP, and TSS concentrations and fluxes (i.e., loads) were evaluated for the period from 2008 to 2022. By starting with 2008, the analysis could evaluate trends since the baseline year of 2008 for P reduction targets in Lake Erie (Annex 4, 2015). Concentrations and fluxes were estimated using the weighted regressions on time, discharge, and season (WRTDS) model. The WRTDS model 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 was designed to provide internally consistent estimates of the actual history of concentrations and fluxes and eliminate the influence of interannual 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.

The WRTDS model was used to make estimates of SRP, TP, and TSS concentrations for each day of the period at each site. These estimated daily concentrations were multiplied by the respective daily mean streamflow to produce an estimate of the daily flux (i.e., load). Using these estimates, flow normalized (FN) concentrations and fluxes were computed using the EGRET R package (R. Hirsch, DeCicco, & Murphy, 2023). FN concentrations and fluxes were used for trend analysis.

The smoothing process that allows flow normalization to provide the best trend evaluation, also means flow normalization doesn’t provide the most accurate estimates of nutrient concentrations and loads (Rowland et al., 2021). 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 compare concentrations from before and after the nutrient management regulations and provide the reader with an idea of variability the actual annual flux values over the period.

To investigate changes in SRP, TP, and TSS before and after the Ohio regulations were implemented in 2015, we calculated flow-weighted mean SRP, TP, and TSS concentrations for each site, period, and season (Frozen, Thaw, Spring application, or Fall application). Then, the values were compared pre- and post-regulation using percent change in flow-weighted mean concentration.

To evaluate trends in SRP, TP, and TSS since the baseline year, daily FN flux estimates were summarized into 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*.

In addition to the trends in annual FN values from 2008-2022, trends in annual SRP, TP, and TSS fluxes were also estimated for the periods of 2008-2015 and 2015-2022. The trends across each period were compared to further elucidate the influence of nutrient reduction strategies since the 2015 nutrient management regulations were implemented. 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). Trends in Spring FN fluxes were also estimated for both the longer-term and the two short-term periods. Spring was set for March 1 through July 31 because spring P 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

## Frozen soil conditions

The average soil frost-in period for winters from December 2008 through April 2022 was 74 days, with a minimum of 33 days and a maximum of 118 days. Frost in dates ranged from 24 November to 18 January and frost-out ranged from 22 December to 27 March. Notably, two winters (2019 and 2020) were split into two frozen periods. When frozen periods were split, the nonfrozen connecting period was set as a thaw period. The frozen period contained 660 days during the pre-regulation period and 455 days during the post-regulation period. The thaw period contained 208 days during the pre-regulation period and 217 days during the post-regulation period. The nonfrozen period (spring and fall) contained 1964 days during the pre-regulation period and 1975 days during the post-regulation period.

Across sites, the thaw season generally contained the highest daily flows and was followed by the spring, frozen, and fall seasons in descending order (Table 2). Although the thaw season contained the highest daily flows, the short time of thawing resulted in the thaw containing the lowest percentage of the total water volume released during both the pre- and post-regulation periods (Table 2). Meanwhile, the spring season contained the highest percentage of water volume. On average, the thaw, frozen, spring, and fall seasons contained 17, 23, 36, and 24 % of the water volume released from the four watersheds.

Table 2: Summary of daily flows for each site, season, and period combination including mean daily discharge (cms) and percentage of stream discharge released within each season and period (%).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Site | Season | Mean daily flow (cms) | | Percent of total water volume released (%) | |
| pre | post | pre | post |
| Tiffin | Frozen | 14 | 11 | 28 | 17 |
|  | Thaw | 30 | 23 | 19 | 16 |
|  | Spring | 15 | 17 | 34 | 39 |
|  | Fall | 5 | 7 | 18 | 28 |
| Blanchard | Frozen | 12 | 12 | 27 | 22 |
|  | Thaw | 27 | 18 | 19 | 15 |
|  | Spring | 12 | 13 | 29 | 37 |
|  | Fall | 6 | 5 | 25 | 26 |
| Maumee | Frozen | 222 | 218 | 28 | 20 |
|  | Thaw | 462 | 352 | 18 | 15 |
|  | Spring | 257 | 275 | 36 | 38 |
|  | Fall | 81 | 107 | 19 | 27 |
| Raisin | Frozen | 28 | 24 | 25 | 17 |
|  | Thaw | 66 | 50 | 19 | 16 |
|  | Spring | 34 | 39 | 34 | 41 |
|  | Fall | 13 | 14 | 22 | 27 |

## Summary of Pre- and Post-Regulation Phosphorus Concentrations

Within the Maumee River watershed, flow-weighted mean concentration reductions were most apparent during the frozen and thaw seasons (Table 3). The Tiffin watershed had 20, 13, and 12% reductions in SRP, TP and TSS, respectively, during the frozen season. While the Blanchard watershed had a 10% reduction in TP and a 33% reduction in TSS during the frozen season. One exception was the 8% increase in SRP concentration in the Blanchard River. During the thaw season, the Tiffin River 11, 0, and 10% concentration reductions in SRP, TP, and TSS, respectively; while, the Blanchard River had 10, 8, and 27% reductions in SRP, TP, and TSS concentration, respectively. These concentration changes, along with those from other, unmeasured tributaries, culminated in concentrations reductions of 20, 17, and 26% for SRP, TP, and TSS, respectively, during the frozen season and 10, 10, and 27% concentration reductions in SRP, TP, and TSS, respectively, during the thaw season. Unlike the observations in the Maumee River watershed, the only mean concentration reduction in the River Raisin was the 1% reduction in SRP during the frozen season. Otherwise, TP concentrations increased 11 and 15% in the frozen and thaw seasons, respectively. While the TSS concentrations increased 22 and 3% in the frozen and thaw seasons, respectively.

While concentration reductions were broadly observed in the frozen and thaw seasons for the Maumee River basin, the spring and especially the fall seasons included more concentration increases. In the spring, the Blanchard River had concentration increases of 17, 13, and 17% for SRP, TP, and TSS, respectively, while the Tiffin River had concentration decreases of 20, 17, and 26% for SRP, TP, and TSS, respectively (Table 3). In the Maumee River, the spring season had an 8% concentration decrease in SRP, but 13 and 6% increases in TP and TSS, respectively. Meanwhile, the River Raisin had concentration increases of 14, 41, and 41% for SRP, TP, and TSS, respectively. In the fall season, Tiffin, Blanchard, and Maumee experienced concentration increases for SRP, TP, and TSS ranging from a 7% increase in TP for Blanchard to a 29% increase in TSS for Tiffin. Alternatively, the Raisin River experienced concentration decreases for TP and TSS in the fall, and a 4% concentration increase in SRP.

Table 3: Summary of average daily flow-weighted mean SRP, TP, and TSS concentrations (mg/L) for each site, season, and period combination.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Season | Station | SRP | | | TP | | | TSS | | |
| pre | post | % change | pre | post | % change | pre | post | % change |
| Frozen | Tiffin | 0.09 | 0.07 | -20 | 0.25 | 0.21 | -13 | 52 | 46 | -12 |
| Blanchard | 0.13 | 0.14 | 8 | 0.46 | 0.41 | -10 | 129 | 86 | -33 |
| Maumee | 0.11 | 0.09 | -20 | 0.44 | 0.36 | -17 | 159 | 117 | -26 |
| Raisin | 0.04 | 0.04 | -1 | 0.14 | 0.16 | 11 | 40 | 48 | 22 |
| Thaw | Tiffin | 0.06 | 0.06 | -11 | 0.27 | 0.27 | 0 | 91 | 82 | -10 |
| Blanchard | 0.11 | 0.10 | -10 | 0.55 | 0.50 | -8 | 197 | 145 | -27 |
| Maumee | 0.08 | 0.08 | -10 | 0.47 | 0.43 | -10 | 199 | 146 | -27 |
| Raisin | 0.04 | 0.04 | 3 | 0.18 | 0.20 | 15 | 60 | 62 | 3 |
| Spring | Tiffin | 0.11 | 0.09 | -20 | 0.44 | 0.36 | -17 | 159 | 117 | -26 |
| Blanchard | 0.11 | 0.13 | 17 | 0.44 | 0.50 | 13 | 136 | 159 | 17 |
| Maumee | 0.08 | 0.08 | -8 | 0.37 | 0.42 | 13 | 154 | 164 | 6 |
| Raisin | 0.03 | 0.03 | 14 | 0.13 | 0.19 | 41 | 44 | 61 | 41 |
| Fall | Tiffin | 0.08 | 0.09 | 9 | 0.23 | 0.27 | 15 | 52 | 68 | 29 |
| Blanchard | 0.17 | 0.18 | 8 | 0.40 | 0.43 | 7 | 79 | 86 | 9 |
| Maumee | 0.10 | 0.11 | 12 | 0.31 | 0.35 | 13 | 89 | 101 | 13 |
| Raisin | 0.05 | 0.05 | 4 | 0.16 | 0.16 | -4 | 40 | 36 | -10 |

## Annual flow-normalized trends, 2008-2022

### Soluble Reactive Phosphorus

The Blanchard River had a 128% increase in annual FN SRP concentrations and a 33% increase in the annual FN SRP load. Meanwhile, the Tiffin River had a 7% decrease in both FN SRP concentration and FN SRP load (Table 4, Figure 1). In the Maumee River, there was slight 0.5% increase in annual FN SRP concentration, but a 6% decrease in annual FN SRP load. Compared to the Ohio sites, the Raisin River displayed 69 and 21% increases in FN SRP concentration and loads, respectively.

Table 4: SRP trends from 2008 to 2022.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Site | FN Concentration of SRP | | | FN Flux of SRP | | | |
| Annual mean in 2008, mg/L | Change, 2008 - 2022 | | Total annual flux in 2008, metric ton/yr | Total annual yield in 2008, kg/km2/yr | Change, 2008-2022 | |
| mg/L | % | kg/km2 | % |
| Tiffin | 0.05 | -0.004 | -7 | 25 | 24 | -2 | -7 |
| Blanchard | 0.10 | 0.13 | 128 | 38 | 42 | 12 | 33 |
| Maumee | 0.07 | <0.001 | 0.5 | 601 | 37 | -2 | -6 |
| Raisin | 0.02 | 0.01 | 69 | 28 | 10 | 2 | 21 |

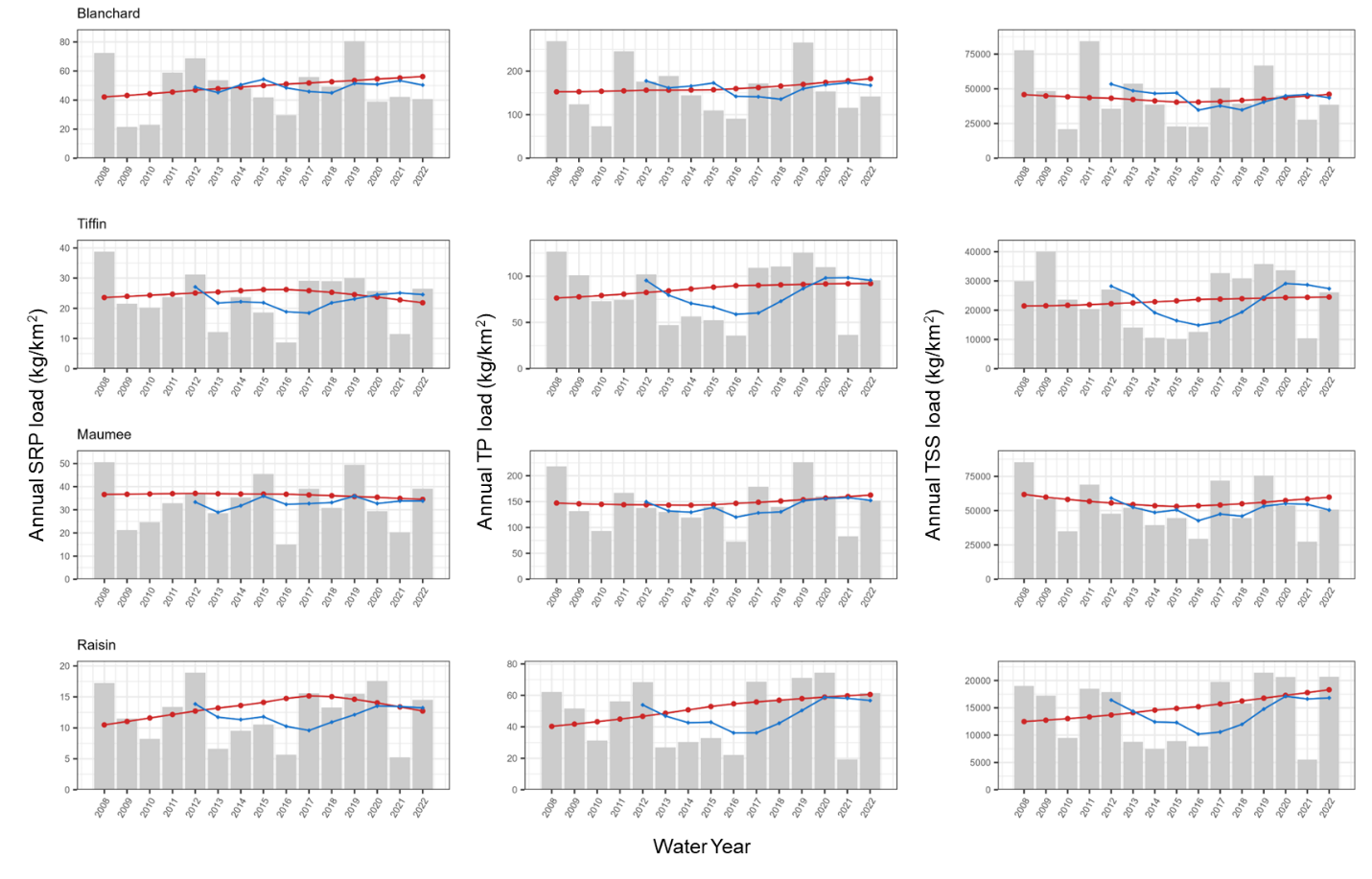


Figure 1: Annual SRP, TP, and TSS loads (kg/km2) for the entire period of interest (2009-2021) across all sites. The gray bars in panels are the WRTDS Kalman Filter results. Red line shows the WRTDS flow normalized results. The Blue line shows the 5-year moving average of “actual” annual SRP loads.

### Total Phosphorus

Annual FN TP concentrations had likely or highly likely upward trends at all four sites with percent changes ranging from 6% at the Maumee site to 63% at the Blanchard site (Table 5). Similarly, for annual FN TP loads, all four of the sites had either very likely or highly likely upward trends with percent changes ranged from 11% at Maumee to 50% at Raisin (Table 5 & Figure 1). Tiffin, Maumee, and Raisin sites had greater increases in load than in concentration, while the Blanchard site had a lower increase in load than in concentration.

Table 5: TP trends from 2008 to 2022.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Site | FN Concentration of TP | | | FN Flux of TP | | | |
| Annual mean in 2008, mg/L | Change, 2008 - 2022 | | Total annual flux in 2008, metric ton/yr | Total annual yield in 2008, kg/km2/yr | Change, 2008-2022 | |
| mg/L | % | kg/km2 | % |
| Tiffin | 0.16 | 0.01 | 6 | 81 | 76 | 19 | 21 |
| Blanchard | 0.24 | 0.15 | 63 | 137 | 153 | 25 | 20 |
| Maumee | 0.23 | 0.01 | 6 | 2413 | 147 | 15 | 11 |
| Raisin | 0.08 | 0.03 | 39 | 109 | 40 | 20 | 50 |

### Total Suspended Solids

Annual FN TSS concentrations decreased in the Maumee River basin with 5% decreases in both the Blanchard and Tiffin Rivers and an 11% decrease in the Maumee River. Unlike the Maumee River basin, annual FN TSS concentrations increased by 27% in the River Raisin (Table 6). Unlike annual FN TSS concentrations, both internal Maumee River watersheds (Tiffin and Blanchard) showed an increase in annual FN TSS loads. While the two sub-watersheds showed an increase in TSS loads, the Maumee River watershed had a 3% decrease in FN TSS loads from 2008 to 2022 (Table 6 & Figure 1). As with FN TSS concentration, the River Raisin had a highly likely upward trends with a 47% increase in FN TSS loads.

Table 6: TSS trends from 2008 to 2022.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Site | FN Concentration of TSS | | | FN Flux of TSS | | | |
| Annual mean in 2008, mg/L | Change, 2008 - 2022 | | Total annual flux in 2008, metric ton/yr | Total annual yield in 2008, kg/km2/yr | Change, 2008-2022 | |
| mg/L | % | kg/km2 | % |
| Tiffin | 48 | -2 | -5 | 22,800 | 21,500 | 3,570 | 14 |
| Blanchard | 40 | -2 | -5 | 41,100 | 45,800 | 180 | 0.5 |
| Maumee | 73 | -8 | -11 | 1,013,500 | 61,800 | -2,020 | -3 |
| Raisin | 22 | 6 | 27 | 33,700 | 12,500 | 5,820 | 47 |

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

For SRP, FN load percent changes were lower since 2015 for all sites (Figure 2). At Maumee, Tiffin, and Raisin, the slope in FN SRP load flipped from a positive to a negative slope, indicating a reduction in FN SRP loads since the implementation of nutrient management regulations. Meanwhile, at Blanchard, the slope in FN SRP load was only a lower positive slope, indicating a continued increase in FN SRP loads since 2015, albeit a lower rate of increase. For TP, two sites (Tiffin and Raisin) had lower slopes in FN loads during recent years, while the other two sites (Blanchard and Maumee) flipped from a negative to a positive slope (Figure 2). Although both Tiffin and Raisin had lower slopes, they were still positive in recent years. For TSS, Blanchard, Maumee, and Raisin had increases in the slope of FN TSS loads since 2015. Only Tiffin showed a reduction in the slope of the FN TSS load. Notably, both Maumee and Blanchard changed from a reduction in FN TSS loads prior to 2015 to an increase in FN TSS after 2015. No site showed a reduction in FN TP or TSS loads since 2015.

Chart, line chart

Description automatically generated

Figure 2: Comparison of slopes in the FN load trends for SRP, TP, and TSS between the pre period (2008-2015) and the post period (2015-2022) for each site. Trends are in units of percent change per year.

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

The P fluxes released during the spring season ranged from 49 to 52% of the annual SRP FN flux (Table 7). 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.

Over the entire period of record, spring SRP FN fluxes decreased by 9 and 10% at Tiffin and Maumee, respectively and increased by 33 and 22% at Blanchard and Raisin, respectively (Table 7). From 2009 to 2015, spring SRP FN fluxes increased at three of the four sites, with only Maumee showing a decrease. The greatest of these upward trends occurred at the Raisin site (35%). 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.

Table 7: Overview of SRP FN flux trends 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 | Percentage of annual FN trend |  | | FN flux trends | |
| Pre  (2008-2015) | Post  (2015-2021) | | Whole Period (2008-2022) |
| Tiffin | 51 | 7 | -15 | | -9 |
| Blanchard | 49 | 19 | 12 | | 33 |
| Maumee | 52 | -3 | -7 | | -10 |
| Raisin | 51 | 36 | -10 | | 22 |

# Discussion

This study indicated that the nutrient management regulations have likely had a mixed effect on P and TSS export into the WLEB. For the positive effects, we observed a decrease in the daily flow-weighted SRP, TP, and TSS concentrations during both the frozen soil and thaw seasons, which is consistent with the expectations of the 2015 nutrient management rules (Table 3). Additionally, there was a decline in FN SRP flux in the Maumee River basin from 2008 to 2022 and within that change, a greater rate of decline since the nutrient management regulations were implemented (Table 7). Furthermore, where TP and TSS delivery increased in the Maumee River basin, this increase was still lower in magnitude than the increase observed in the River Raisin over the same period suggesting that actions to reduce nutrient loss in the Maumee River basin may be mitigating increases even though reductions are not being observed. Although positive effects were observed, these positive effects were not observed in all sub-watersheds of the Maumee River. Moreover, the declines in P and TSS delivery to the Maumee River and subsequently the WLEB during frozen and thaw periods appear to be moderately counteracted by increased P and TSS delivery during the spring and fall seasons. Increases in FN TP delivery in all watersheds suggests that the recently implemented nutrient reduction strategies have either a) only had a mitigating effect on TP losses within the basin or b) have actively increased the amount of TP released from non-point sources. Outside of positive or negative effects, the differences between concentration and flux changes over the period allowed for an investigation into the relationship between flow condition and phosphorus delivery. Finally, it should be mentioned that the trends present herein are subject to uncertainty and the relatively small percent changes have the potential to offset by estimation errors.

## Influence of nutrient management regulations on P and TSS delivery

### Improvement in Maumee River Basin

The nutrient management regulations appear to have a reduced the amount of SRP, TP, and TSS delivered to the WLEB from the Maumee River during frozen and thaw periods, along with trend of decreasing spring SRP loads. We expected phosphorus concentrations, especially SRP concentrations, to decline during the frozen and thaw seasons in response to restriction on manure application on frozen or snow-covered soils. Our results matched these expected outcomes with SRP and TP concentrations in the Maumee River being reduced by 20 and 17%, respectively, during the frozen season and 10 and 10%, respectively, during the thaw season (Table 3). Relative to the Maumee River, the River Raisin either experienced increases or smaller reductions in flow-weighted mean SRP and TP concentrations during the frozen and thaw seasons (Table 3). Additionally, the Tiffin River – a large sub-watershed of the Maumee River – also experienced similar reductions in the SRP, TP during the frozen and thaw seasons after the nutrient management regulations were implemented (Table 3). For context, similar nutrient management regulations were implemented in 2011 in the much smaller Grand Lake St. Mary’s watershed and that watershed experienced reductions in flow-weighted mean SRP concentrations ranging from 18% during high flows to 48% during low flows during the winter ban period (Jacquemin et al., 2018).

Furthermore, we found increasing reductions in spring SRP fluxes after 2015 in both the Tiffin River (7% increase during the pre-period and a 15% reduction during the post-period) and the Maumee River (a 3% decrease during the pre-period increasing to a 7% reduction during the post-period) (Table 7). Taken together, these results suggest a basin wide pattern in reducing winter and spring nonpoint nutrient pollution in response to the nutrient management regulation. In accordance with reductions in frozen and thaw season concentrations, there was also the potential to find small annual reductions in SRP load because frozen soil and thaw seasons are linked to periods of high flow (Table 2). The results matched this expectation with annual FN SRP loads in the Maumee River switching from a slight annual increase from 2008-2015 to a slight annual decrease from 2015 to 2022 (Figure 2). This switch to a decline in annual FN SRP loads is significant, especially when considered against the 20.0 kg km-2 increase (109%) in FN SRP fluxes from 1995 to 2015 in the Maumee River (Choquette et al., 2019).

### Potential changes in Application Timing

While SRP and TP concentrations decreased within the Maumee River during the frozen, thaw, and spring seasons, flow-weighted mean SRP and TP concentrations increased (12 and 13%, respectively) during the fall application season (from 1 Jul until the soil freezes) (Table 3). A similar increase was observed in both the Tiffin and Blanchard Rivers. Additionally, flow-weighted mean SRP concentrations increase by 44% during medium flows and stayed constant with a 0% change during high flows during the manure application period in the Grand Lake St. Mary’s watershed. These increases suggest that the banning of manure application on frozen soils likely does not reduce the amount of manure applied to the land. Instead, the bans may simply shift application timing. We hypothesize that the fall increases were a product of more manure is now being applied during the fall season before the soil freezes to ensure that the lagoons and waste holding facilities can hold all the manure produced during the winter. While the impact of increased fall application can be mitigated by the lower flow conditions during the fall, this work around has the potential to limit the effectiveness of a winter manure application ban on annual P loads.

### Did solids release increase in response to incorporation incentive?

Another concern of the regulations was the potential for an increase in TSS and particulate P export from fields due to the exception for nutrient application if the nutrients were quickly incorporated to the frozen soils. Increased incorporation could increase the potential for soil erosion from tilled fields during subsequent precipitation events. However, our results showed that, along with the declines in SRP and TP concentrations during the frozen and thaw seasons, flow-weighted mean TSS concentrations also decreased during these seasons within the Maumee River Basin. The Tiffin, Blanchard, and Maumee Rivers had declines of 12, 33, and 26%, respectively during the frozen season and 10, 27, and 27%, respectively, during the thaw season (Table 3).

## Changes in Nutrient and Sediment Delivery at the Annual Time Scale.

### Annual trends in the Maumee River

While seasonal trends allowed for an investigation into the likely effectiveness of the nutrient management regulation, annual trends give us a chance to investigate the progress of nutrient reduction strategies, including the nutrient management regulations, to meet the annual target reductions provided in the GLWQA. From 2008 to 2022, the Maumee River showed a 6% decline in the annual FN SRP flux but an 11% increase in the annual FN TP flux. The 6% (2 kg km-2) decline in annual FN SRP flux indicated that progress is being made towards the goal of a 40% reduction in annual SRP loads, but that this progress was well below expectations. Although annual FN TP loads increased, the 15 kg km-2 increase estimated for the Maumee River was well below the 20 kg km-2 increase estimated for the reference River Raisin, which indicated that the nutrient reduction strategies implemented in the Maumee River watershed may at least be mitigating the increase in TP observed in other parts of the WLEB.

### Blanchard vs. Tiffin

Within the Maumee River watershed, the Tiffin and Blanchard Rivers showed divergent trends in annual SRP and TP fluxes. The Tiffin River exhibited similar trends to the Maumee River with a 7% decrease in SRP, while the Blanchard River had a 33% increase in SRP. From Table 1, both the Tiffin and the Blanchard watersheds have a similar size and percentage of agricultural areas. One potential cause of this difference was the difference in livestock population dynamics within the two watersheds. From 2012 to 2017, the number of cattle and hogs decreased by 9917 and 211 animals, respectively, in the Tiffin River watershed (NASS data – cite). Meanwhile, over the same span, the number of cattle and hogs increased by 16,749 and 47,954 animals, respectively, in the Blanchard River watershed (NASS data – cite). Thus, there could have been similar implementation, but simply more manure and therefore more nutrient export in the Blanchard River. Alternatively, these results could be indicative of heterogenous implementation throughout the watershed that may temper the amount of influence that nutrient reduction strategies at the field scale can have at the large watershed scale. Further investigation is needed to elucidate causes of the different results in the two otherwise similar watersheds.

### Influence of flow condition

While 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 and flux trends are biased toward high flow observations (Sprague et al., 2011). Thus, the slight increase in FN SRP concentrations paired with the decrease in FN SRP fluxes at Maumee suggests that the reductions in SRP delivery are occuring predominately during high flow conditions (Table 4). Other sites like Blanchard and Raisin followed a similar pattern, except that increases in FN SRP concentrations were greater than those of FN SRP fluxes. Unlike SRP, TP showed the opposite trend with greater increases in FN flux relative to FN concentration, which suggests that the greater proportion of increased delivery is occuring during high flows. Tiffin and Raisin had a similar pattern.

Taken together, these results suggest that SRP is disproportionately being either released more or being reduced less during low flows, while TP is disproportionately being either released more or being reduced less more at high flows. Notably, differences between concentration and flux changes for TSS match those of TP. The greater delivery of soluble P during low flows may be a product of the changing nutrient application timing with more manure being spread in the fall, when flows are generally lower. Meanwhile, the greater amount of particulate loss during high flow events may be the product of more extreme events or changes in farming practices in recent years. Both TP and TSS showed decline in the Maumee River before 2015 (Figure 2) and this highlights the need to determine why particulate losses have increased in recent years.

## Implication of results on ability to meet reduction targets

Relative to P reduction targets in the WLEB, the reductions in both SRP and TP concentrations during the frozen, thaw, and spring application seasons paired with the downward trends in both annual and springtime SRP fluxes in the Maumee River and the Tiffin River (a smaller tributary of the Maumee) indicate that the nutrient management regulations have helped to mitigate SRP delivery to the WLEB. However, increases in SRP and TP concentrations during the fall low flow periods suggest that the nutrient management regulations likely do not reduce the annual amount of nutrients being added to the fields, but simply alters the timing of application. While this can help to reduce seasonal loads, especially the spring SRP loads that heavily influence algal bloom size, it is unlikely to provide substantial P reductions by itself. Furthermore, the consistently positive changes in annual FN 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 Tiffin and Blanchard watersheds are both of similar size and located within the overall Maumee River watersheds. Future research is needed to determine exactly 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 2008, but the increase in livestock during this period in the Blanchard River suggests that even with nutrient management regulations in place, if you add more manure to the fields, you are likely to increase the amount of P exported from the watershed.

# Conclusion

As we continue to develop methods to reduce nutrient export, it is imperative that we quantify the influence of these practices on nutrient export and their relative influence on our progress towards nutrient reduction goals. By comparing flow-weighted mean concentrations before and after nutrient regulations, we were able to show that nutrient management regulations can reduce SRP, TP, and TSS during the seasons in which they are implemented. However, our results also showed that nutrient regulations can have an adverse effect on SRP, TP, and TSS export during periods outside the purview of the regulations. By estimating the FN SRP, TP, and TSS fluxes, this study showed that progress towards reducing SRP export in the Maumee River at both seasonal and annual timescales. However, these improvements did not span all constituents of interest as annual TP and TSS fluxes increased across the sites, especially in recent years. Taken together, our results indicated the nutrient regulations reduced P export at varying spatial and temporal scales but that combinations of poor implementation, confounding factors, and legacy P have led to heterogenous success and limited progress towards meeting basin-wide P reduction targets.

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