# Evaluating Management Options to Reduce Lake Erie Algal Blooms with Models of the Maumee River Watershed

FINAL REPORT | NOVEMBER 2019

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## About this report:

This report summarizes the findings from a three year project funded by the Ohio Department of Higher Education Harmful Algal Bloom Research Initiatives. The project was managed by The Ohio State University and included partners from the University of Toledo, LimnoTech, Heidelberg University, the University of Michigan, and the United States Geological Survey.

The cover background was generated using Google Earth imagery in the ggmap package of R Statistics and combining with NASA MODIS sattellite image from 2015.

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# Executive Summary

## I. PROJECT MOTIVATION

Algae blooms in Lake Erie are fed by nutrients entering through tributaries. These blooms often produce toxins that threaten potable water and recreation, and cause the depletion of oxygen needed by fish and other aquatic organisms. To reduce the extent of Lake Erie's algal blooms and these negative impacts, the United States and Canada signed a binational executive agreement – the Great Lakes Water Quality Agreement of 2012 (GLWQA) – to reduce the amount of phosphorus entering the lake by 40%.

The Maumee River delivers the majority of external phosphorus loads to western Lake Erie (Figure ES1). Around 80% of the watershed is used for agriculture and more than 85% of the phosphorus loads come from nonpoint sources[i]. Thus, much of the effort to reduce phosphorus loads in this watershed focuses on agricultural practices.

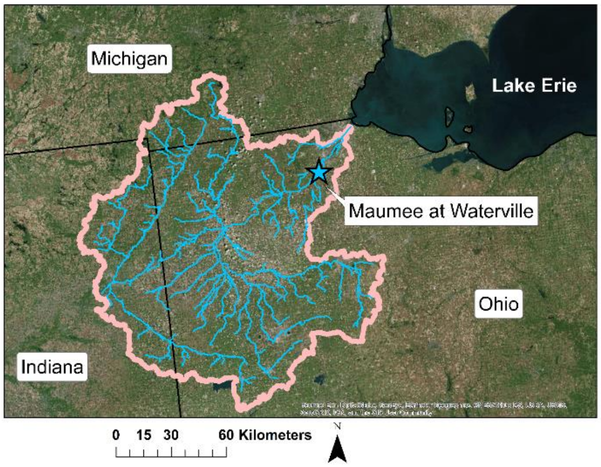

Figure ES1. The map shows the boundary, rivers, and tributaries within the 4.2 million acre (17,000 km$^2$) Maumee River watershed. This area spans the states of Indiana, Michigan, and Ohio with its outlet in the western Lake Erie basin. Data collected from the USGS gauge in Waterville, Ohio was used for model calibration and validation.

Management options in the Maumee River watershed were evaluated by several research teams, led by The Ohio State University (Figure ES2). Researchers used five watershed models to establish baseline conditions, simulate 13 sensitivity analyses to determine the effects of practices, and then simulate 5 bundled management scenarios, which included a variety of different management practices and adoption rates. This research was supported by the Ohio Department of Higher Education Harmful Algal Bloom Research Initiative. Additionally, feedback was received from a stakeholder advisory group throughout the project.

Figure ES2. The five research institutions, led by The Ohio State University, independently developed watershed models that were used to evaluate management scenarios.

## II. WATERSHED TARGETS

The GLWQA of 2012[ii] and subsequent U.S. action plan[iii] set reduction targets for two forms of phosphorus delivered from the river over two time periods in a given year. Dissolved Reactive Phosphorus (**DRP**) is a portion of the Total Phosphorus (**TP**), and each is related to different concerns arising from algae blooms. The March-July (*i.e.,* spring) DRP and TP loads affect the magnitude of toxic-producing algal growth found in the nearshore and western Lake Erie basin. Alternatively, October-September (annual) TP loads are associated with the oxygen depletion that occurs in the central basin. For each of these targets, a 40% load reduction from the amounts observed in 2008 (water year) was set, which is expected to reduce algal bloom size below nuisance levels.[1] This equates to 860 metric tons of TP and 186 metric tons of DRP in March-July loading, as well as 2287 metric tons of TP in annual loading from the Maumee River watershed.

It was established that these goals should be reached in 9-out-of-10 years in recognition that an especially wet year may produce a bloom regardless of management efforts. Given recent trends of increased precipitation and discharge, an alternative metric to judging success was also proposed: the flow-weighted mean concentration (FWMC; further referred to as concentration). In this computation, the load is divided by the amount of water discharged from the Maumee River. For the March-July period, the targets are 0.23 ppm TP and 0.05 ppm DRP. Using this guideline allows us to judge the success of management practices independent of the amount of rainfall that occurs in a given year.

## III. WATERSHED MODELS

Our five models were configurations of the Soil & Water Assessment Tool (SWAT) using publicly available data to generate a baseline simulation spanning 10 years (2005-14). This baseline assumed existing management practices of cover crop implementation on cover crop implementation on 8% (range: 6-10%); buffer strips on 31% (29-34%); tile drainage on 75% (72-77%); continuous no-tillage on 32% (22-37%); and seasonal no-tillage on 42% (22-63%) of cropland, average across the five models.

An initial set of scenarios (1-13) was simulated to evaluate the impacts of practices with widespread adoption rates. Following discussions with the stakeholder group, additional scenarios were run with adoption rates that are expected to resemble realistic goals. Each scenario was evaluated for the ability to meet watershed targets for March-July TP and DRP loads in 9-out-of-10 years, as well as concentration targets.

## IV. SOURCE CONTRIBUTIONS

Among the initial sensitivity analyses, we evaluated contributions from point sources (primarily wastewater treatment plant effluent and sewer overflows) as well as manure applications on farmland. Averaging simulated impacts across the five models and the ten-year period we found that:

- Eliminating all point source discharges resulted in reductions of 4.5% of TP and 9.2% of DRP loads on average during March-July. Concentrations declined by 2.9% and 7.3%, respectively.
- Eliminating phosphorus from manure applications resulted in reductions of 7.4% TP and 8.0% DRP loads on average during March-July. Concentrations declined by 7.7% and 8.5% respectively. For reference, manure accounted for ~11% of phosphorus fertilizer applied in the watershed.

## V. MODIFIED FERTILIZER APPLICATION

Several sensitivity analyses examined the effects of fertilizer application rates, types, methods, and timing on phosphorus loads. Averaging simulated impacts across the five models over the ten-year period we found that:

- Altering the timing of manure application between the spring and fall had only slight (≤ ±1.1%) effects on March-July TP and DRP loading with the exception that if all manure was applied in spring, DRP loads increased by 2.7% and its concentration increased by 2.4% over the baseline.
- Decreasing phosphorus applied in the forms of manure and mineral fertilizers by 25% resulted in reductions of 8.2% TP and 11% DRP loads during March-July. Concentrations declined by 8.4% and 11%, respectively.
- Broadcasting all fertilizers with no incorporation resulted in increases in March-July TP (9.3%) and DRP (13%) loads. Incorporation following the broadcast of fertilizers resulted in a slight decrease of these loads (≤ 0.9%). Subsurface placement of all fertilizer – injecting below the top soil layer that interacts with surface runoff – had the greatest effect and reduced TP (18%) and DRP (23%) loads during March-July, compared to the baseline.
- Combining adjustments to rate (reducing fertilizer application by 50%), placement (all subsurface), and timing (all fertilizer applied in the fall) yielded a decrease of TP (26%) and DRP (31%) loads during March-July.

## VI. BEST MANAGEMENT PRACTICES

The remaining sensitivity analyses evaluated effects of individual best management practices with 100% adoption rates, and we found that:

- Drainage water management applied in all tile drained areas (78% of cropland) had a negative impact on the TP and DRP loads which increased by 9.2% and 8.6% during March-July, respectively, but was one of the most impactful practices for limiting nitrogen export from farmland.

- Headwater wetlands placed in all subbasins and sized at roughly 1% of the subbasin area with the assumption that they received half of all drainage water resulted in reductions of TP loads by 17% and the DRP load by 7.1% during March-July. However, the longevity of the wetlands was not examined.
- Cereal rye cover crops grown on all fields (increased from the existing level of being applied to 8% of cropland) reduced the TP load by 35% and the DRP load by 8.1% during March-July.

## VII. BUNDLED PRACTICE SCENARIOS

Following the initial set of sensitivity analyses, five scenarios were developed with stakeholder guidance that focused on simulating the effects of implementing realistic adoption rates of management practices. Previous modeling efforts have shown that placing management in areas contributing high phosphorus load per unit area can result in greater simulated benefits compared to random allocation of management efforts, this approach is called "targeted management."

As a frame of reference, measured data showed the March-July TP and DRP target loads were met in 3 years out of the 10 years simulated during baseline conditions. In our first bundled management scenario Scenarios were simulated that altered management practices on cropland using random and targeted approaches.

- In our first bundled management scenario (14, Figure ES3), we increased adoption rates for cover crops (to 58%), subsurface placement (to 50%), and buffer strips (to 78%) using random placement across the watershed. Results from the multi-model average predicted that the March-July targets should be met between 5 and 6 years for TP; and 4 years for DRP. March-July concentrations decreased by 26% for TP and 17% for DRP.
- The second bundled scenario (15) used the same management practices as the first (14), but the practices were targeted to fields with the greatest phosphorus loss. Results of the multi-model average predicted that the March-July load targets should be met 8 out of 10 years for TP and 4 out of 10 years for DRP. March-July concentrations decreased by 41% for TP and 27% for DRP.
- The third bundled scenario (16) was guided in part by survey data regarding adoption rates of practices that are most likely in the near future. Thus, adoption of cover crops was increased to 60%; subsurface placement to 68%; and buffer strips to 50% using a targeted-implementation approach. Results from the multi-model average predicted March-July load targets should be met between 7 and 8 years for TP, and 4 and 5 years for DRP. March-July concentrations decreased by 38% for TP and 21% DRP.
- In the fourth bundled scenario (17), cover crop adoption was increased to 58% and subsurface application to 50% of all cropland, and headwater wetlands were included in 78% of the subbasins using a targeted management approach. The multi-model average predicted March-July targets should be met between 6 and 7 years for TP and 5 and 6 years for DRP. March-July concentrations decreased by 37% for TP and 22% for DRP.
- In the fifth bundled scenario (18), cover crop adoption was increased to 50%; subsurface placement to 60%; no-tillage to 50%, and drainage water management to 15% of tile-drained cropland with a targeted management approach. The multi-model average predicted March-July targets should be met between 6 and 7 years for TP and 5 years for DRP. March-July concentrations decreased by 32% for TP and 23% for DRP.

Targets for March-July TP and DRP loads were not met in 9-out-of-10 years by the multi-model average of any of the scenarios. However, as presented here scenarios 15 and 18 reached the targeted March-July TP flow-weighted mean concentration.

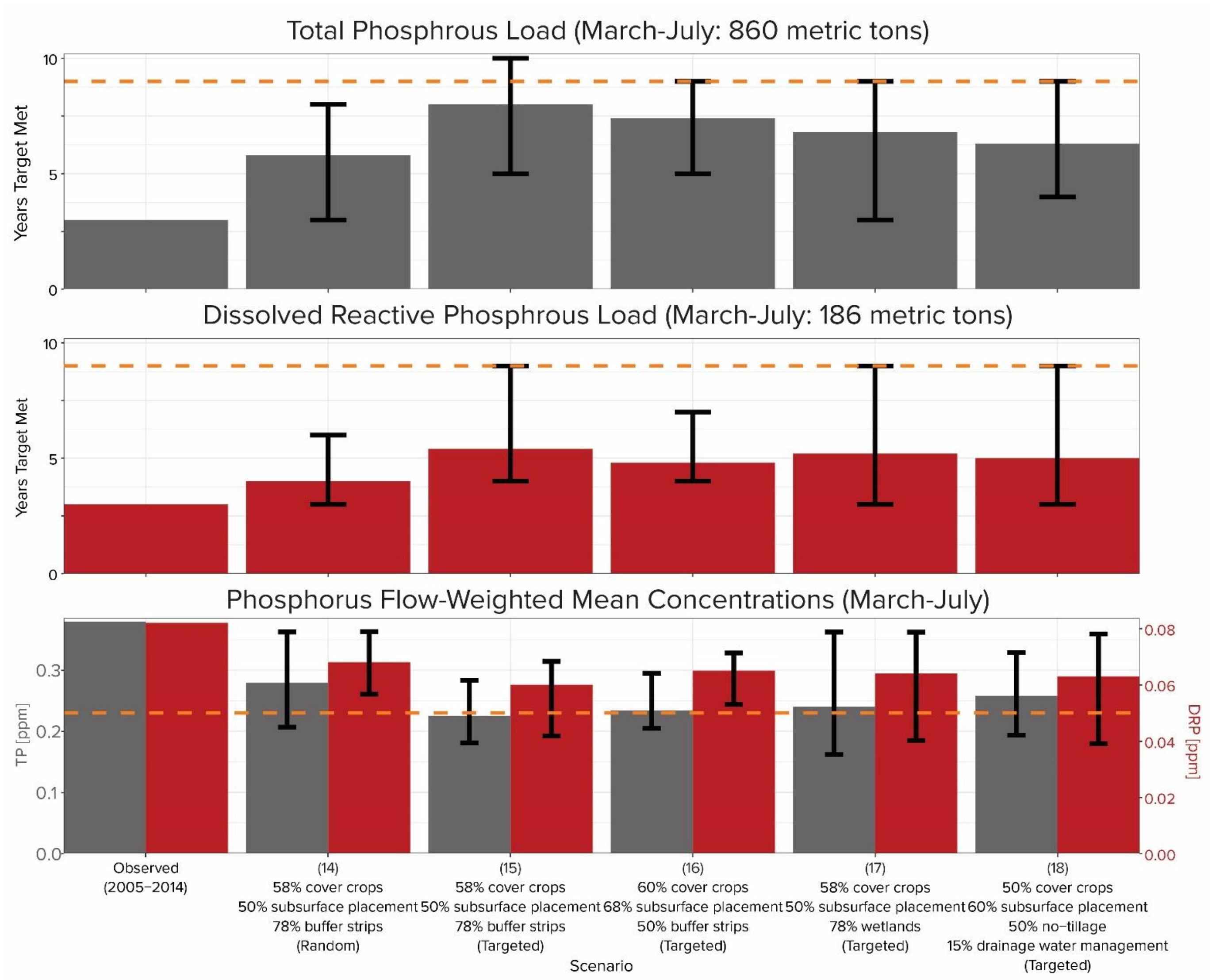

Figure ES3. Modeling results of the bundled management scenarios were compared to the March-July TP (gray) and DRP (red) loading targets set by the Great Lakes Water Quality Agreement. Bars showed the average number of years that targets were met by each model and whiskers denote the range of these results. Flow-weighted mean concentration targets for March-July TP and DRP are shown on the bottom panel. Bars denote the average concentration and whiskers show the range for the individual models. The orange, dashed line represents the targets set by the GLWQA. To meet the target requires a result at or above the orange line for the top two graphs of "years met," while a value below the orange line in the third plot meets the concentration target.

## VIII. CONCLUSIONS

The results of the model simulations demonstrate that some individual and bundled management practices can provide substantial reductions in TP and DRP loads and concentrations. However, they also demonstrate that greater adoption rates of the practices beyond those in the bundled scenarios, and/or alternative practices may be needed to meet the watershed targets.

Meeting the DRP targets was especially challenging although subsurface placement of fertilizers produced the greatest reductions of DRP. Notably, the 10-year simulated period had three years in which DRP loads exceeded that of 2008. This means that a reduction of 40% would not have achieved the 9-out-of-10 year DRP goal. Using the concentration metric as a reference is a more accurate way of judging the impacts that management scenarios

## IX. SUMMARY POINTS FROM TWO MULTI-MODEL STUDIES

Watershed models can be used to test a variety of “what if” scenarios that include management options to help identify strategies potentially capable of achieving water quality targets. They can simulate the effects of management strategies by estimating impacts on crop yields and water quality. Watershed models can be used to explore the impacts of historical and projected future conditions. In the current project and in our previous project (http://graham.umich.edu/water/project/erie-western-basin), we used and compared results from five SWAT models to increase confidence in project findings.

- The results of the previous project suggest that it may be possible to meet GLWQA TP and DRP target loads **on average over ten years**, using widespread implementation and increased adoption of conservation practices. The current project highlights the need for combinations of practices and greater rates of adoption (more than 50 to 58%) to meet these targets **9 out of 10 years**.
- Results from the previous project suggested that there are multiple pathways and approaches through bundling practices that should be able to reach the TP and DRP load and concentration targets on average over ten years, including scenarios focused on working land practices. While none of these scenarios met these targets in 9-out-of-10 years in the current project, they were capable of producing two thirds of the required March-July DRP concentration reductions required to reach the target of 0.05 ppm.
- While loading targets may be pragmatic ways for managers and the public to consider the potential of management plans, results from the current project make it clear that concentrations can provide additional quantification and understanding of past and potential reductions.
- Results of model scenarios indicate that the DRP load target is generally more difficult to reach than the TP load target. Part of this is due to the March-July DRP target being a more challenging goal than the other targets. In the ten-year simulation period, achieving the March-July DRP target in 9-out-of 10 years required a 43% reduction, whereas the other three targets (TP annual and March-July, and DRP annual) required a 32-39% reduction.
- Results of model simulations indicate that DRP is more difficult to decrease than TP, as the majority of practices were more promising for TP than for DRP. Results support the finding that practices that reduce or intercept erosion, such as cover crops and buffer strips, are much more effective at reducing TP than DRP. Nutrient management practices were important for both TP and DRP, and subsurface placement of phosphorus fertilizers was found to be one of the most effective practices for reducing DRP losses throughout the watershed.
    - Subsurface placement of fertilizers was notably effective in reducing phosphorus loads. It was simulated in our models by placing of 99% of fertilizer beneath the top soil layer (1 cm), which interacts with surface runoff, and the method did not reduce residue levels, increase erosion, or accelerate runoff.
    - The rate, placement, and timing scenario was used to represent 4R practices across the watershed and resulted substantial reductions. Fertilizer and manure application rates were also considered, and while important, manure was not found to be as large of a contributor to phosphorus loadings as inorganic fertilizers.
- Watershed models can help identify key areas and the most important conservation actions. Results show that when effective practices, such as subsurface placement, cover crops, buffer strips, and headwater wetlands, are placed in (or intercept, in the case of wetlands) field areas that have the highest potential P loss, there is a greater effectiveness in reducing watershed level P outputs than to randomly take actions throughout the watershed. This finding was in the absence of variable soil test phosphorus values in the models; greater benefits may be realized if fields having higher soil phosphorus concentrations were treated. Results from the watershed models indicated reductions of 9% in DRP and 14% for TP with a targeting approach compared to a random approach, even at large adoption rates. However, field-level information and one-on-one conservation planning is

needed to determine where to place the practices and apply them to the most critical source areas in the landscape.

- In the current project, producer surveys were used to determine the existing level of conservation practice implementation as well as what levels of adoption are feasible. This information was used to guide development of more realistic scenarios. For example, the surveys indicated that it may be feasible to reach 60% adoption (50-54% increase) of cover crops and 68% adoption (12-68% increase) of subsurface placement, and these were used along with 50% adoption of buffer strips (16-21% increase) as a feasible bundled scenario.
- As in the previous study, the current project included rigorous and transparent communication with a broad stakeholder group. Input from these external advisors guided decisions about how to approach the modeling in order to produce meaningful, more realistic scenarios. These advisors can also guide successful approaches to communication and outreach.
- Continued modeling work of Lake Erie watersheds will provide additional insight and support continued adaptive management approaches as new data and management alternatives become available.

## REFERENCES

[i] Nutrient Mass Balance Study for Ohio's Major Rivers;
https://epa.ohio.gov/Portals/35/documents/Nutrient%20Mass%20Balance%20Study%202018_Final.pdf.

[ii] Great Lakes Water Quality Agreement;
https://binational.net//wp-content/uploads/2014/05/1094_Canada-USA-GLWQA-_e.pdf.

[iii.] US Action Plan for Lake Erie;
https://www.epa.gov/sites/production/files/2018-03/documents/us_dap_final_march_1.pdf.

# Project Introduction & Methods

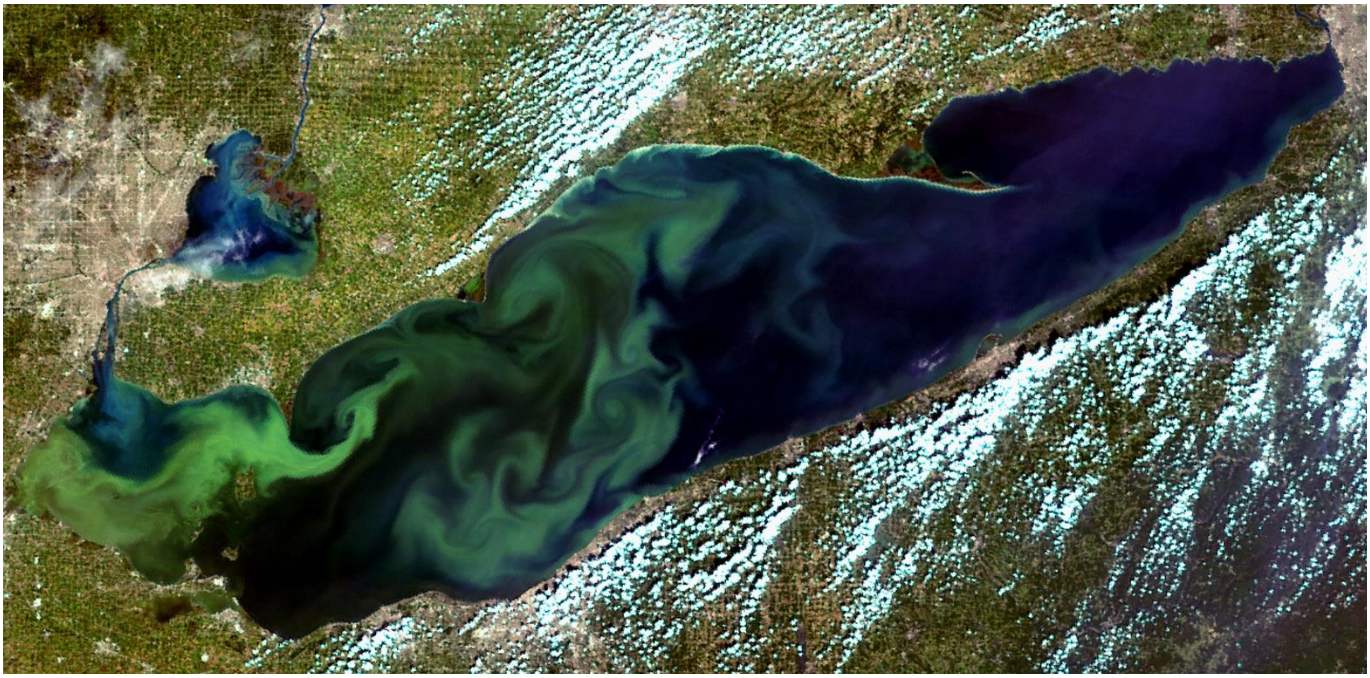

Figure 1. Image of a Lake Erie algae bloom in 2015 taken with the MODIS sensor on the NASA Terra satellite.

## LAKE ERIE ALGAL BLOOMS

Coastal eutrophication occurs when excessive inputs of nutrients cause algal blooms (Figure 1)[2], hypoxia, and other associated problems, and it is one of the greatest environmental challenges facing society.[3] Impacts of coastal eutrophication include degraded water quality,[4] reduced and contaminated fisheries,[5, 6] threats to irrigation and potable water supplies,[7] and decreases in tourism, cultural activities, and coastal economies.[4, 8] These impacts have been observed in western Lake Erie since the mid-1990s. Since then, harmful algal blooms (HABs) and hypoxia have returned to the lake, driven largely by increased dissolved reactive phosphorus (DRP) inputs.[9, 10] Reducing eutrophication in Lake Erie, and globally, requires, in part, a decrease in anthropogenic nutrient inputs to coastal ecosystems.[11] The establishment of nutrient thresholds has been recommended as an important step in this effort.[12]

In 2012, the United States and Canada revised nutrient loading targets for Lake Erie in the Great Lakes Water Quality Agreement.[13] Since then, the challenge has been to determine what management practices and levels of implementation are needed to reach these thresholds. This information is critical as basin-wide plans and policies are developed to reduce downstream eutrophication and algal blooms. As part of that that effort, this report describes the continued and improved use of multiple watershed models, guided by stakeholder input, to analyze the potential ability of watershed-scale management actions to reach the prescribed phosphorus reduction targets for western Lake Erie. Because it builds upon and complements a past study, results are compared to this previous work.[14]

## WATERSHED TARGETS

The Great Lakes Water Quality Agreement set reduction targets for two types of phosphorus loads over two time periods in a given year: Total

Phosphorus (TP) and Dissolved Reactive Phosphorus (DRP). Both the TP and DRP loads during March-July affect the development of toxic-producing cyanobacteria in the nearshore and western Lake Erie basin. Annual water year (Oct.-Sept.) TP loads cause the oxygen depletion that occurs in the central basin. For all of these loads, targets were set at a 40% reduction from the loads observed in 2008. This reduction is expected to reduce the size of algal blooms below nuisance levels. This equates to 860 metric tons of TP and 186 metric tons of DRP in March-July loading, as well as 2287 metric tons TP in annual loading, from the Maumee River watershed.[13]

It was established that these goals should be met in 9-out-of-10 years because management efforts may not be sufficient in an especially wet year. As climate variability is expected to increase in the future, an alternative approach to judge success was also included: flow-weighted mean phosphorus concentrations (FWMC; further referred to as concentration). In this measurement, the load is normalized by the amount of water discharged from the Maumee River. For the March-July period this equates to a target of 0.23 ppm **TP** and 0.05 ppm **DRP**. This threshold allows evaluation of the success of management practices adjusted for the amount of rainfall that occurs in a given year.

While the updated GLWQA has defined standards for phosphorus loads, there are additional concerns about the nitrogen-to-phosphorus (N:P) loading ratio. Specifically, the toxicity of HABs may be increased by greater N:P ratios.[15-17] Therefore, we also considered the impacts that practices had on nitrogen and the N:P ratios in nutrient loads.

## MAUMEE RIVER WATERSHED MODELS

Watershed models offer an opportunity to predict impacts of agricultural management approaches for varying levels of adoption based upon field research observations. Significant knowledge of management and climate impacts on field-scale nutrient runoff has been gained from edge-of-field research in the western Lake Erie basin.[18-20] Yet these studies are not easily extrapolated to predict the effects of management across the entire watershed. Watershed models have been utilized for this role,[4] and the Soil Water Assessment Tool[21] (SWAT) that was used for this study has been widely employed in agricultural watersheds, such as the Maumee River watershed where our previous modeling studies have focused.[14, 22] The SWAT watershed model is appropriate for modeling the Maumee River watershed because it offers the greatest ability to represent relevant agricultural management practices.[23]

The 4.2 million acre (17,000 $km^2$) Maumee River watershed is one of the largestest sources of P to Lake Erie and a primary driver of the extent of Lake Erie HABs (Figure 2).[9, 10] Following the success of point source management to address Lake Erie eutrophication in the 1970s and 1980s,[24] the focus changed to reducing nonpoint source emissions, primarily from agriculture. Studies have reported that 89% of the total phosphorus discharged from the Maumee can be attributed to nonpoint sources[9] within a watershed comprised of >70% agricultural land use. For this reason, we focused our evaluation on agricultural management practices to reduce phosphorus loads. It is likely that a combination of infield and edge-of-field practices will be needed to meet reduction targets.[14, 19] Therefore, the approach we have taken is to estimate the impacts of bundled (combined) management practices at varying adoption levels in several models simulating loading in the Maumee River watershed.

The benefits of a multi-model approach include viewing problems from various conceptual and operational perspectives, providing multiple lines of evidence, and decreasing decision risk with different model assumptions, parameterization and routines.[14] While multiple models have successfully been applied to lakes and estuaries beginning in the 1970s,[25-27] our group was the first to apply this approach to evaluate policy-relevant land management scenarios aimed at addressing coastal eutrophication.[14] For this study, we used five independently developed SWAT models of the Maumee River watershed. Each model is considered

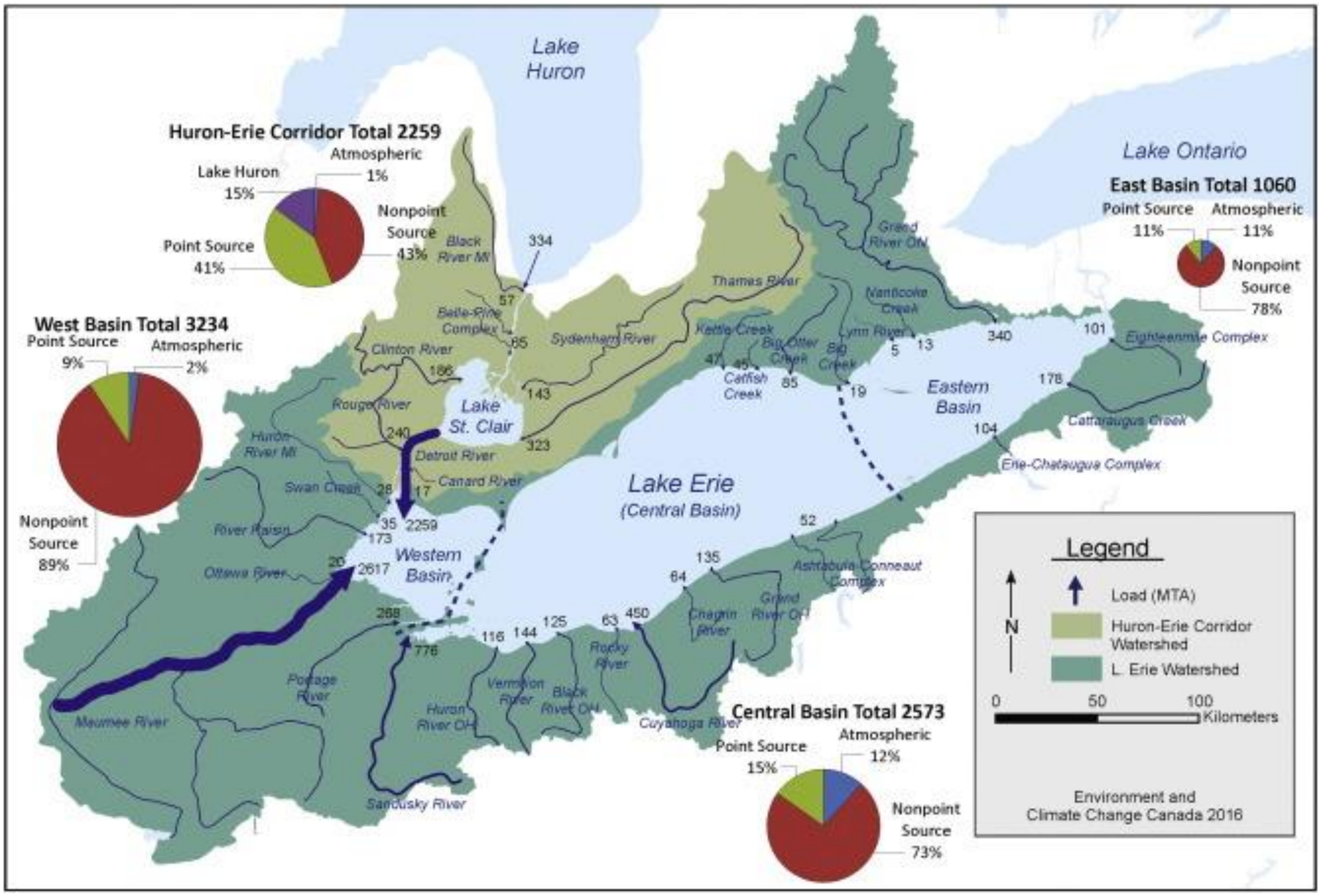

Figure 2. Estimates of annual total phosphorus loading from the tributaries and sources to Lake Erie. Loads were averaged over the 2003-2013 period. The Maumee River and watershed are part of the western Lake Erie basin. *From: Maccoux et al. 2016* [8]

unique due differences in decisions made by independent modeling groups regarding spatial resolution, data sources, subroutines, land management operations, and model parameterization and calibration (Appendix 1).

## STAKEHOLDER ADVISORY GROUP

In spite of advocacy and efforts to broaden the use of environmental models to evaluate management scenarios, challenges remain in engaging stakeholders to increase the understanding, application and support for modeling analyses.[28] This issue is especially relevant for modeling studies addressing eutrophication of coastal water bodies that can be disconnected from upstream stakeholder communities. Representation from these and other stakeholders is especially important because they are often responsible for taking the actions needed to improve downstream conditions. For instance, the Ohio Domestic Action Plan (2018)[29] specifies several management actions to be implemented in Lake Erie watersheds to reduce nutrient runoff reaching Lake Erie. To address gaps in model understanding and application in the Lake Erie watershed, our goal was to co-produce knowledge[30] with scientists and stakeholders to develop and evaluate potential management scenarios for their ability to reach nutrient reduction goals for Lake Erie.

The stakeholder group (Table 1) collaborated with the modeling team throughout the project to guide the development of the models and selection and interpretation of management scenarios to be tested. Similar to past projects that engaged stakeholders representing a variety of organizations,[14, 22] we sought to form a broad stakeholder group for this project to make the results more relevant and impactful on decision-making, as recommended by *Garb et al.* (2008).[31] The resulting stakeholder group included representation from agricultural groups, government agencies, nongovernmental organizations, and environmental groups.

While the stakeholders provided input throughout this study, specific contributions included improvement of baseline data incorporated into the models, development of final scenarios and scenarios analyzing the sensitivity of management practices, identification of possible scenarios for the future, development of improved comparisons to the recommended phosphorus loading targets, and interpretation and dissemination of results and recommendations. Advances to the models based on stakeholder input included improved data and spatial application of manure and inclusion of existing management practices from U.S. Department of Agriculture (USDA) survey data.[32] Collaboration with stakeholders continued through the end of the project and included interpretation of results, outreach, and the writing of this report.

Table 2. Organization represented in the stakeholder advisory group.

| | | |
|---|---|---|
| USDA-NRCS | Joyce Foundation | Ohio Soybean Council |
| Ohio Farm Bureau Federation | Ohio Department of Agriculture | Ohio Environmental Council |
| OSU Extension | Ohio EPA | Ohio Pork Council |
| Ohio Dairy Producers Association | Blanchard River Watershed Partners | Defiance Soil and Water Conservation District |
| Environmental Defense Fund | The Nature Conservancy | National Wildlife Federation |
| Alliance for the Great Lakes | | Ohio Corn and Wheat |

## SCENARIO SELECTION

Combined input from stakeholders and surveys led to more feasible scenarios compared to those evaluated in the past. Collaboration between modelers and stakeholders also identified scenarios of interest for which limitations of the existing SWAT models prohibited analysis. These potential management scenarios involved improvements in soil health, such as increased organic matter, and application of fertilizer to match crop removal rates. An improved comparison of the scenario results to reduction targets was also realized based on stakeholder requests to better reflect the intentions of the GLWQA reduction goals.

During the first stakeholder and modeler meeting in September of 2016, the project was introduced, and the current versions of the models were described, which included model improvements following the past project.[14] These improvements included better representation of stormwater discharges (Appendix 2), and inclusion of existing BMPs in baseline SWAT models. The stakeholders also provided new data sources that further improved the spatial application of manure (Appendix 3). During this meeting, the stakeholders and modelers collaborated to select an initial set of sensitivity analyses and scenarios (Table 2) that would be completed to provide results to guide the later selection of bundled scenarios. While the large increases in adoption are unlikely to be realized, the goal was to assess their maximum impact to determine if these practices would be helpful to include in later bundled scenarios at more realistic adoption rates. Scenario 1 (No Point Source Discharges) evaluated the impact of eliminating phosphorus from point source effluent to estimate the relative contributions of phosphorus from these sources. Scenarios 2-10 evaluated variations in manure and fertilizer applications that included elimination of manure application and changes in methods of applications. Scenarios 11-13 evaluated the impacts of maximum implementation of cover crops, drainage water management, and headwater wetlands.

During the second stakeholder and modeler meeting in March of 2017, results of the initial scenarios and sensitivity analyses were reviewed and interpreted, and the final bundled scenarios were selected (Table 2). To provide consistency and comparison with our previous results, similar scenarios from our past modeling analyses were reevaluated with the current models. This included Scenarios 14 (In-field & Buffers- placed randomly throughout the cropland in the watershed) and 15 (In-field & Buffers – placed randomly) with increased the adoption of cover crops, subsurface placement of fertilizer (below 1 cm), and buffer strips. Because other studies, including our past work, have documented better performance of targeted management practices;[14] modelers and stakeholders agreed targeted options for all other scenarios (15-18). The on scenario 16 (Likely Adoption of-field and Buffers) to develop a likely adoption scenario with feasible future adoption rates based on surveys and stakeholder input.

Table 2. Sensitivity analyses and scenarios included in the model simulations.

| ID | | | Description | Purpose |
|---|---|---|---|---|
| **1** | Sensitivity Analyses | No point source discharge | 100% point source P removal | source contribution |
| **2** | | No manure application | 100% removal of P from manure (baseline N application maintained) | source contribution |
| **3** | | 25% P rate reduction | 25% less P fertilizer applied | management effect |
| **4** | | Broadcast P | All fertilizer is broadcast without incorporation | management effect |
| **5** | | Broadcast and incorporated P | All fertilizer is broadcast with incorporation | management effect |
| **6** | | Subsurface applied P | All P fertilizer is subsurface applied (99% below top 1 cm of soil) | management effect |
| **7** | | Fall manure | All manure applied in fall | management effect |
| **8** | | Spring manure | All manure applied in spring | management effect |
| **9** | | Fall and spring manure | Manure applied half in spring and half in fall | management effect |
| **10** | | Rate, placement, and timing | Fertilizer and manure P applications decreased by 50% and sub-surface applied in the fall | management effect |
| **11** | | Cereal rye cover crop | Cover crops on 100% of cropland | management effect |
| **12** | | Controlled drainage | Drainage water management in 100% of tile-drained areas | management effect |
| **13** | | Headwater wetlands | Wetlands in all subbasins receive 50% of flow | management effect |
| **14** | Bundled Scenarios | In-field + Buffers (Random) | 58% cover crops + 50% subsurface placement + 78% buffer strips | scenario, random implementation |
| **15** | | In-field + Buffers | 58% cover crops + 50% subsurface placement + 78% buffer strips | scenario, targeted implementation |
| **16** | | Likely Adoption of In-field + Buffers | 60% cover crops + 68% subsurface placement + 50% buffer strips | scenario, survey data, targeted implementation |
| **17** | | In-field + Wetlands | 58% cover crops + 50% subsurface placement + 78% wetlands | scenario, targeted implementation |
| **18** | | In-field + Controlled drainage | 50% cover crops + 60% subsurface placement + 50% no-tillage + 15% drainage water management | scenario, targeted implementation |

# Results

## MODEL CALIBRATION

Similar to our previous modeling project,[14, 23, 33] the models were validated using data collected near the watershed outlet (Waterville, OH; USGS Gauge #04193500). However, in this project all models used the same precipitation, temperature, and point-source discharge data from 2005-2014, which was also the period for which management scenarios were analyzed. Model validation was evaluated using statistical tests, including Nash-Sutcliffe efficiency (NSE) and percent bias (PBIAS), for monthly flow and loads of TP, DRP, and total nitrogen (TN). Values for these statistical tests were mostly within recommended levels[34] for SWAT model validation of the five models (Table 3). Simulated multi-model averages compared favorably to measured annual loads (2005-2015) of TP and DRP, although this comparison revealed a bias of over-predicting DRP at lower loads (Figure 3). This over prediction was also reflected in the results from the baseline scenario, which predicted greater TP and DRP loads during March-July compared to measured data. Additionally, “soft calibration”[35, 36] demonstrated general agreement between modeled results and water budgets from edge of field data[37] and crop yields (Appendix 4).

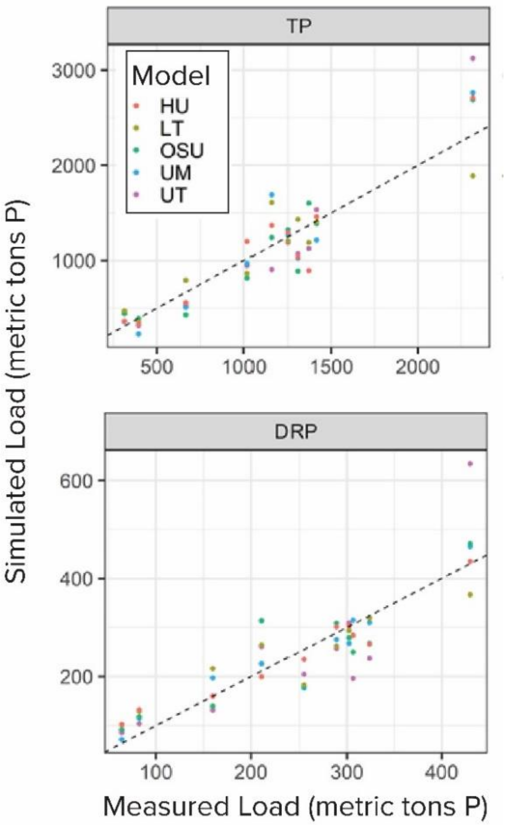

Figure 3. Comparison of simulated versus measured data revealed a bias of over predicting Dissolved Reactive Phosphorus (DRP) at lower loads, but general agreement for TP and DRP between 2005-2014.

Table 3. Modeling teams and validation results for SWAT watershed models (names of institution are bolded) compared to standards* established by *Moriasi et al.* (2007) for percent bias (PBIAS) and Nash-Sutcliffe Efficiency (NSE).

| | | Standards* for good performance | **Multi-Model Average** | Ohio State University | University of Toledo | Heidelberg University | LimnoTech | University of Michigan |
|---|---|---|---|---|---|---|---|---|
| PBIAS (%) | Discharge | +/- 10 | 2.2 | -3 | 0.1 | 2 | 11 | 1 |
| | TP | +/- 25 | -2.7 | 19 | -13 | -7 | -13 | 1 |
| | DRP | +/- 25 | 5 | -4 | 32 | 7 | -15 | 7 |
| NSE | Discharge | > 0.65 | 0.89 | 0.99 | 0.83 | 0.88 | 0.91 | 0.94 |
| | TP | | 0.70 | 0.71 | 0.66 | 0.73 | 0.77 | 0.61 |
| | DRP | | 0.67 | 0.73 | 0.50 | 0.77 | 0.67 | 0.69 |

## SENSITIVITY ANALYSES & SCENARIOS

The 13 sensitivity analyses (Scenarios 1-13) were not considered implementable strategies, rather they were intended to determine the impacts of individual practice and use this to inform the final scenarios. This included the effects of changing or eliminating nutrient sources; the effect of fertilizer application rates, timing, and methods; and individual best management practices (BMPs). Each model was evaluated independently as to whether it reached the watershed target for March-July TP and DRP loads. This "success rate" was then averaged across the five models (Figure 4). Additionally, we considered the percent reduction in the flow-weighted mean concentrations for both TP and DRP for March-July across the models and years (Figure 5). Comparison among simulated concentrations provides a good visual result of practice impacts. Finally, we also evaluated changes in the TP:TN loading ratios (Figure 6).

## SOURCE CONTRIBUTIONS

The elimination of point sources of phosphorus (Scenario 1, No Point Source Discharges, Table 4) reduced the average concentration of TP by 5% and DRP by 9% during March-July (Figure 3), showing agreement with (less than 1% difference from) the previous project.[14] The elimination of all phosphorus manure application (Scenario 2, No Manure Application) yielded 7% reductions in TP, and 8% reductions in DRP concentrations.

## MODIFIED FERTILIZER APPLICATION

A 25% reduction in P applied in inorganic fertilizer and manure (Scenario 3, 25% P Reduction) resulted in an 8% reduction in TP, and an 11% reduction in DRP concentrations. Broadcast application of all inorganic fertilizer and manure (Scenario 4, Broadcast P) resulted in a 9% increase in TP and 14%

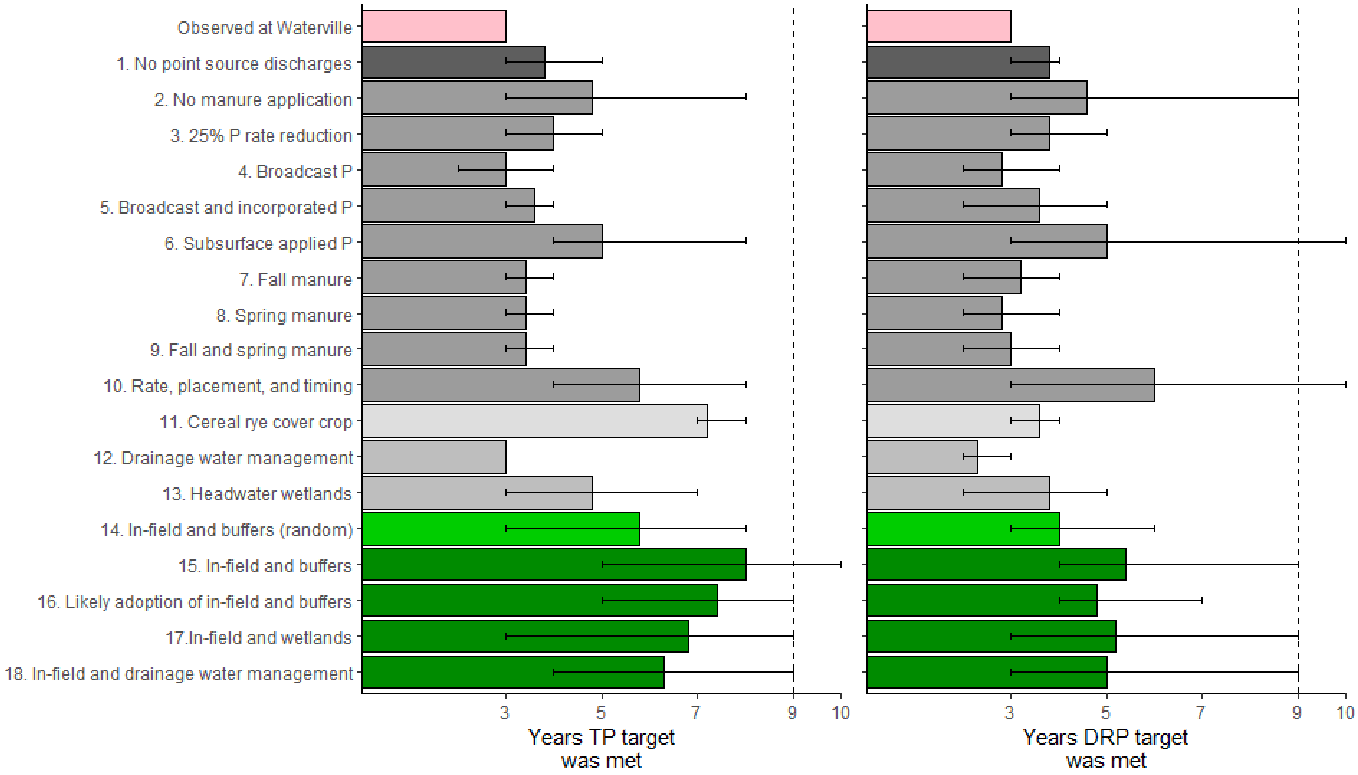

Figure 4. Predicted average number of years from 2005-2014 that analyzed sensitivity analyses and bundled scenarios reached the March-July load goals established by the GLWQA (860 metric tons TP, 186 metirc tons DRP). The GLWQA established a goal of meeting these reductions 9-out-of-ten years, denoted by the vertical dashed line. Whiskers denote the range of results from the five watershed models.

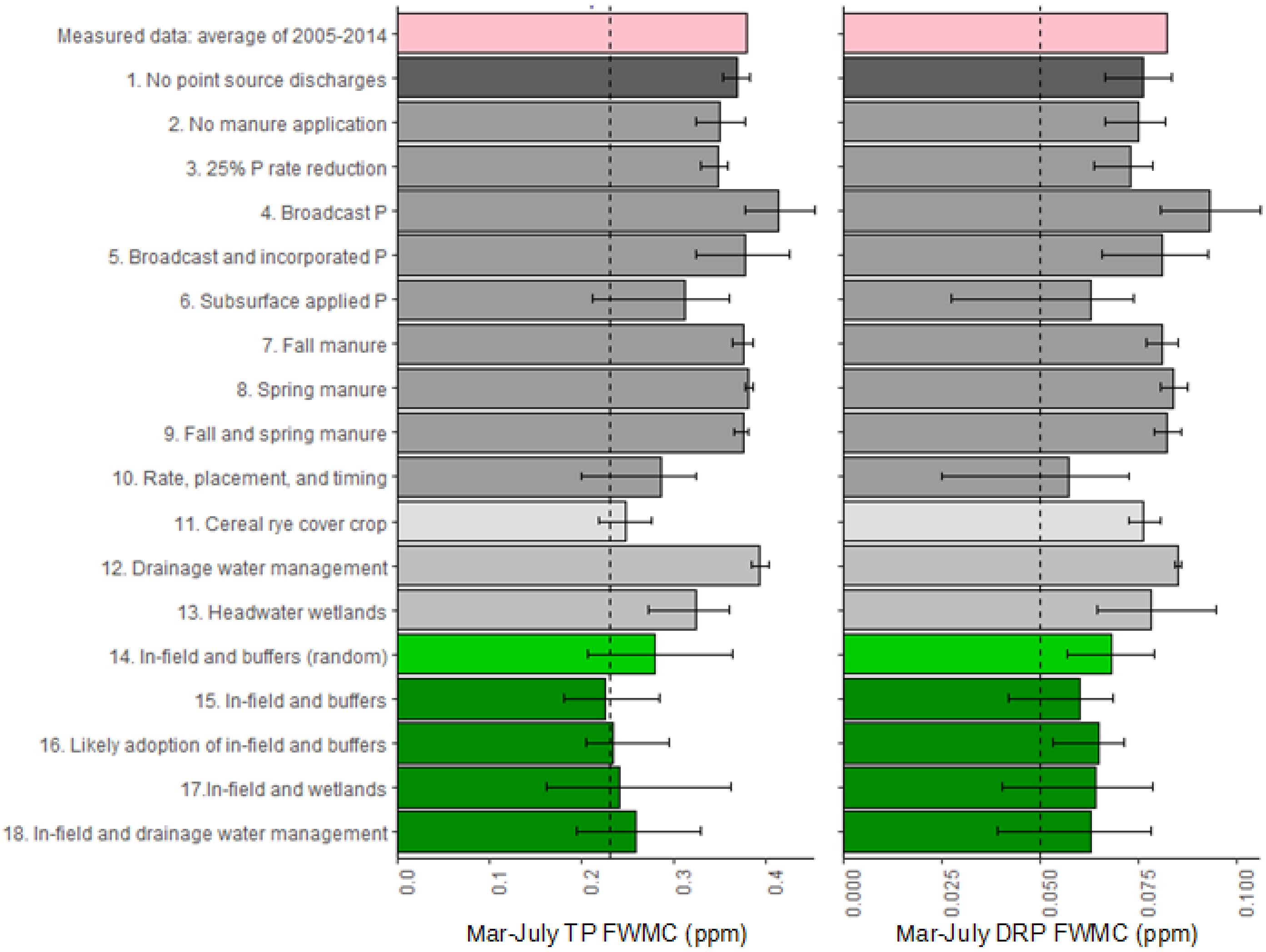

Figure 5. Predicted Flow-Weighted Mean Concentration (FWMC) for Total Phosphorus (TP) and Dissolved Reactive Phosphorus (DRP) from analyzed sensitivity analyses and bundled scenarios compared to the average observed from 2005-2014. Whiskers denote the range of results from the five watershed models. Vertical dashed lines denote reduction targets established in 2016 by Annex IV of the Great Lakes Water Quality Agreement (GLWQA, 0.23 ppm TP, 0.05 ppm DRP).

increase in DRP concentrations. In contrast, if all inorganic fertilizer and manure were subsequently incorporated via tillage (Scenario 5, Broadcast and Incorporated P), the projected decreases in TP and DRP concentrations were 0% and 1%, respectively. Reductions of 18% for TP and 23% for DRP concentrations were found when all fertilizers were injected into the soil (Scenario 6, Subsurface Applied P).

Scenarios testing the timing of manure application changed the phosphorus March-July concentrations in the Maumee River by less than a 3% decrease for TP and a 1% increase for DRP. These three scenarios included all of the manure applied in the fall (Scenario 7, Fall Manure), all of the manure applied in the spring (Scenario 8, Spring Manure), and half of the manure applied in the fall and half in the spring (Scenario 9, Fall and Spring Manure). Scenario 10 (Rate, Placement and Timing), which simulated the combination of subsurface P fertilizer placement, a 50% reduction in P fertilizer application rate, and all fertilizer application in fall, was not substantially more effective (26% TP and 31% in DRP) than subsurface application alone (Scenario 6, Subsurface Applied P).

## BEST MANAGEMENT PRACTICES

We simulated the individual impacts of cover crops, drainage water management, and headwater wetlands in the models. A sensitivity analysis of cover crop adoption on 100% of row crop fields (Scenario 11, Cereal Rye Cover Crop) resulted in decreases of 35% for TP and 8% for DRP concentrations. A scenario of drainage water management in all tile-drained areas (Scenario 12, Controlled Drainage) resulted in average concentration increases of 9% for both TP and DRP. A scenario testing the implementation of a wetland in each sub-watershed (Scenario 13, Headwater Wetlands) resulted in decreases in average concentrations of 17% for TP and 7% for DRP.

## BUNDLED-MANAGEMENT SCENARIOS

While none of the model averages for the final bundled scenarios (Scenarios 15-17) reached the GLWQA March-July target for TP, two scenarios (Scenario 15, In-field and Buffers and Scenario 16, Likely Adoption of In-field and Buffers) approached the TP target with model averages meeting this goal between 7- and 9-out-of-10 years (Figure 4). Some individual models predicted that the targets were met in at least 9-out-of-10 years (Appendix 5, Figure 1) and the average TP concentrations approached the 0.23 ppm P target for scenarios 15 and 16 (Figure 5). Scenarios with in-field practices and wetlands (Scenario 17, In-Field + Wetlands) or drainage water management (Scenario 18, In-Field + Controlled Drainage) reached the TP load reduction goal less than 7-out-of-10 years, and had average concentrations that exceeded the 0.23 ppm target (Figure 5).

None of the model averages met the 9-out-of-10-years goal for DRP during March-July. The best performing scenarios for DRP March-July reduction (Scenarios 15-18) had model averages that reached the reduction target for approximately 50% of the years. While none of the model averages were below the DRP concentration goal of 0.05 ppm, four of the scenarios resulted in DRP concentrations close to this goal, with reductions from the baseline level of 0.08 to near 0.06 ppm. Comparing the TP and DRP results makes it clear that reaching the DRP goal during March-July is more challenging than reaching the TP target.

For TN, the baseline observed concentration was 6.7 ppm and all final scenarios resulted in decreases of 10% or less. Because the percentage of TN reductions were smaller than TP reductions, the TN:TP ratio increased from an observed value of 17.6 to between 22 and 27 for the final scenarios (Figure 6). This demonstrates that these scenarios should have greater potential to reduce phosphorus compared to nitrogen, and raise concerns about past assumptions that implementing BMPs focused on phosphorus will result in similar reductions of nitrogen. The potential role of nitrogen in Lake Erie HABs has recently been examined,[15] and suggests a need to focus on nitrogen reductions in combination with P reductions.

In addition to Scenario 1 (No Point Source Discharges), Scenarios 14 (In-Field and Buffers Random) and 15 (In-Field and Buffers) demonstrated consistency with the past modeling results.[14] Similar model average reductions were found for TP (present: 42%, compared to past: 39%) and DRP (34% compared to 39%). Also similar to past studies and policy recommendations[38] greater reductions were observed for targeted locations of BMP installation compared to random locations. The targeted scenarios were the most effective in our past analysis, and produced reductions in concentration that were below the management target for TP (Figure 5). However, reductions for DRP were not below the target, and only met the loading target reductions 8+ and 5+ years out of ten, respectively for TP and DRP (Figure 4). The less desirable outcomes predicted across all scenarios compared to the past study could in part be a result of the more stringent evaluation goals used in this analysis compared to past watershed modeling study.[14] Another finding congruous with the current and past study is the positive performance of scenarios that included subsurface placement of P fertilizer.[18, 33]

Scenario 16 (Likely Adoption of In-field and Buffers) was constructed to be a more feasible version of Scenario 15 (In-field + Buffers), and the two scenarios produced similar phosphorus loading results. For concentrations of both TP and DRP during March-July, Scenario 15 produced slightly greater reductions that Scenario 16. Comparison of scenarios 16 and 17 (In-field + Wetlands) also offer evidence of the potential to interchange practices across the watershed. Scenario 16 had 78% of buffer strips and Scenario 17 had 78% adoption of wetlands, and both produced similar reductions in TP and DRP from the watershed.

These findings support flexibility in the application of conservation practices across the watershed. Provided practices effective for phosphorus are incentivized, the choice can be tailored based on field characteristics and farmer preferences. Similar reductions can be produced by interchanging management practices.

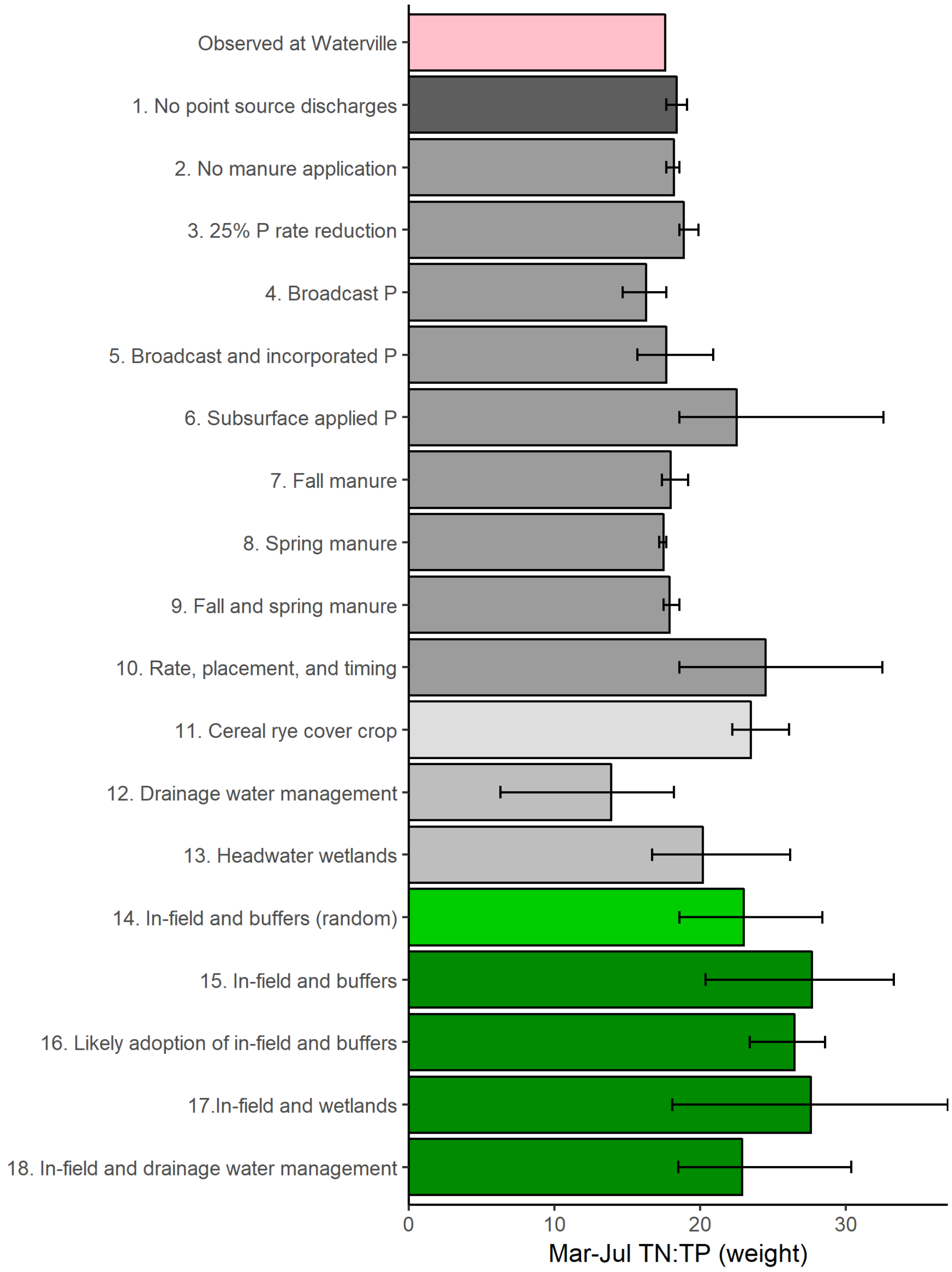

Figure 6. Predicted average Total Nitrogen (TN) to Total Phosphorus (TP) ratios for 2005-2014 resulting from sensitivity analyses and bundled scenarios (March-July). Whiskers denote the range of results from the five watershed models. Increased ratios compared to observed values identify scenarios with greater potential to reduce phosphorus compared to nitrogen.

# Conclusions

Results of this study demonstrate that there are multiple pathways with potential to make progress towards the phosphorus reduction targets specified in the GLWQA. While no scenario produced results that reached the GLWQA reduction targets for 9-out-of-10-years for DRP or TP based on the average from all of the models, it was clear that some scenarios should produce greater reductions in nutrient losses than others. In fact, two scenarios did reach the TP concentration goal. Based on these results, greater adoption rates of the selected practices compared to what was tested here will likely be needed to reach the GLWQA reduction targets. Comparing TP and DRP results demonstrates that reaching the DRP goals for March-July is more challenging than reaching the TP goals.

Considering the reduction in concentrations provided greater insights into the effects of management practices that were not discernable by looking at the 9-out-of-10 year success of the scenarios. By comparing the two types of target reductions included in the GLWQA, it is clear that the 9-out-of-10-year goal is a more difficult goal to reach than the concentration goals given the years chosen for this analysis (2005-2014). While a scenario may be very near meeting the needed reduction for the ninth greatest year, it will simply be shown as meeting the goal 8-out-of-ten-years. In contrast, comparing model results to the concentration targets included in the 2012 GLWQA gives a more detailed understanding of the ability of each scenario to make progress toward these goals. For instance, none of the scenarios met the GLWQA reductions for 9-out-of 10 years (Figure 4), but two of the final scenarios met the GLWQA TP concentration threshold and three more approached the target (Figure 3). Similarly, for DRP, none of the scenarios met the GLWQA targets more than 6-out-of-10 years (Figure 4), but four of the scenarios nearly produced the needed reduction in the DRP concentrations (Figure 3).

While changes in magnitude of annual algal blooms and phosphorus loads may be pragmatic ways for managers and the public to consider the potential of specific management plans, results of this study make it clear that more subtle metrics, like changes in concentration, should also be considered that provide better quantification and understanding of past and potential changes.

# References

1. *US Action Plan for Lake Erie*; https://www.epa.gov/sites/production/files/2018-03/documents/us_dap_final_march_1.pdf.

2. Jill Jentes Banicki NOAA, partners predict large summer harmful algal bloom for western Lake Erie. *Ohio Sea Grant* **2019,** .

3. Paerl, H.W.; Otten, T.G. Harmful Cyanobacterial Blooms: Causes, Consequences, and Controls. *Microbial Ecology* **2013,** *65* (4), 995-1010.

4. Watson, S.B.; Miller, C.; Arhonditsis, G.; Boyer, G.L.; Carmichael, W.; Charlton, M.N.; Confesor, R.; Depew, D.C.; Höök, T.O.; Ludsin, S.A. The re-eutrophication of Lake Erie: Harmful algal blooms and hypoxia. *Harmful algae* **2016,** *56*, 44-66.

5. Bukaveckas, P.A.; Lesutienė, J.; Gasiūnaitė, Z.R.; Ložys, L.; Olenina, I.; Pilkaitytė, R.; Pūtys, Ž; Tassone, S.; Wood, J. Microcystin in aquatic food webs of the Baltic and Chesapeake Bay regions. *Estuar. Coast. Shelf Sci.* **2017,** *191*, 50-59.

6. Wituszynski, D.M.; Hu, C.; Zhang, F.; Chaffin, J.D.; Lee, J.; Ludsin, S.A.; Martin, J.F. Microcystin in Lake Erie fish: Risk to human health and relationship to cyanobacterial blooms. *J. Great Lakes Res.* **2017,** *43* (6), 1084-1090.

7. Lee, J.; Lee, S.; Jiang, X. Cyanobacterial Toxins in Freshwater and Food: Important Sources of Exposure to Humans. *Annual Review of Food Science and Technology* **2017,** *8*, 281-304.

8. Wolf, D.; Georgic, W.; Klaiber, H.A. Reeling in the damages: Harmful algal blooms' impact on Lake Erie's recreational fishing industry. *J. Environ. Manage.* **2017,** *199*, 148-157.

9. Maccoux, M.J.; Dove, A.; Backus, S.M.; Dolan, D.M. Total and soluble reactive phosphorus loadings to Lake Erie: A detailed accounting by year, basin, country, and tributary. *Journal of Great Lakes Research* **2016,** *42* (6), 1151-1165.

10. Scavia, D.; Allan, J.D.; Arend, K.K.; Bartell, S.; Beletsky, D.; Bosch, N.S.; Brandt, S.B.; Briland, R.D.; Daloğlu, I.; DePinto, J.V.; Dolan, D.M.; Evans, M.A.; Farmer, T.M.; Goto, D.; Han, H.; Höök, T.O.; Knight, R.; Ludsin, S.A.; Mason, D.; Michalak, A.M.; Richards, R.P.; Roberts, J.J.; Rucinski, D.K.; Rutherford, E.; Schwab, D.J.; Sesterhenn, T.M.; Zhang, H.; Zhou, Y. Assessing and addressing the re-eutrophication of Lake Erie: Central basin hypoxia. *Journal of Great Lakes Research* **2014,** *40* (2), 226-246.

11. Conley, D.J.; Paerl, H.W.; Howarth, R.W.; Boesch, D.F.; Seitzinger, S.P.; Havens, K.E.; Lancelot, C.; Likens, G.E. Controlling eutrophication: nitrogen and phosphorus. *Science* **2009,** *123*, 1014-1015.

12. Paerl, H.W.; Hall, N.S.; Peierls, B.L.; Rossignol, K.L. Evolving paradigms and challenges in estuarine and coastal eutrophication dynamics in a culturally and climatically stressed world. *Estuaries and Coasts* **2014,** *37* (2), 243-258.

13. *Great Lakes Water Quality Agreement*; https://binational.net//wp-content/uploads/2014/05/1094_Canada-USA-GLWQA-_e.pdf.

14. Scavia, D.; Kalcic, M.; Muenich, R.L.; Read, J.; Aloysius, N.; Bertani, I.; Boles, C.; Confesor, R.; DePinto, J.; Gildow, M. Multiple models guide strategies for agricultural nutrient reductions. *Frontiers in Ecology and the Environment* **2017,** *15* (3), 126-132.

15. Newell, S.E.; Davis, T.W.; Johengen, T.H.; Gossiaux, D.; Burtner, A.; Palladino, D.; McCarthy, M.J. Reduced forms of nitrogen are a driver of non-nitrogen-fixing harmful cyanobacterial blooms and toxicity in Lake Erie. *Harmful algae* **2019,** *81*, 86-93.

16. Steffen, M.M.; Davis, T.W.; McKay, R.M.L.; Bullerjahn, G.S.; Krausfeldt, L.E.; Stough, J.M.A.; Neitzey, M.L.; Gilbert, N.E.; Boyer, G.L.; Johengen, T.H.; Gossiaux, D.C.; Burtner, A.M.; Palladino, D.; Rowe, M.D.; Dick, G.J.; Meyer, K.A.; Levy, S.; Boone, B.E.; Stumpf, R.P.; Wynne, T.T.; Zimba, P.V.; Gutierrez, D.; Wilhelm, S.W. Ecophysiological Examination of the Lake Erie Microcystis Bloom in 2014: Linkages between Biology and the Water Supply Shutdown of Toledo, OH. *Environ. Sci. Technol.* **2017,** *51* (12), 6745-6755.

17. Horst, G.P.; Sarnelle, O.; White, J.D.; Hamilton, S.K.; Kaul, R.B.; Bressie, J.D. Nitrogen availability increases the toxin quota of a harmful cyanobacterium, Microcystis aeruginosa. *Water Research* **2014,** *54* (Supplement C), 188-198.

18. Williams, M.R.; King, K.W.; Duncan, E.W.; Pease, L.A.; Penn, C.J. Fertilizer placement and tillage effects on phosphorus concentration in leachate from fine-textured soils. *Soil Tillage Res.* **2018,** *178*, 130-138.

19. Pease, L.A.; Fausey, N.R.; Martin, J.F.; Brown, L.C. Weather, Landscape, and Management Effects on Nitrate and Soluble Phosphorus Concentrations in Subsurface Drainage in the Western Lake Erie Basin. **2018,** .

20. Pease, L.A.; King, K.W.; Williams, M.R.; LaBarge, G.A.; Duncan, E.W.; Fausey, N.R. Phosphorus export from artificially drained fields across the Eastern Corn Belt. *J. Great Lakes Res.* **2018,** *44* (1), 43-53.

21. USDA Agricultural Research Service; Texas A&M AgriLife Research SWAT - Soil and Water Assessment Tool. **2018,** .

22. Kalcic, M.M.; Kirchhoff, C.; Bosch, N.; Muenich, R.L.; Murray, M.; Griffith Gardner, J.; Scavia, D. Engaging stakeholders to define feasible and desirable agricultural conservation in western Lake Erie watersheds. *Environ. Sci. Technol.* **2016,** *50* (15), 8135-8145.

23. Gebremariam, S.Y.; Martin, J.F.; DeMarchi, C.; Bosch, N.S.; Confesor, R.; Ludsin, S.A. A comprehensive approach to evaluating watershed models for predicting river flow regimes critical to downstream ecosystem services. *Environmental modelling & software* **2014,** *61*, 121-134.

24. Ludsin, S.A.; Kershner, M.W.; Blocksom, K.A.; Knight, R.L.; Stein, R.A. Life after death in Lake Erie: nutrient controls drive fish species richness, rehabilitation. *Ecol. Appl.* **2001,** *11* (3), 731-746.

25. Bierman, V.J. Comparison of Models Developed for Phosphorus Management in the Great Lakes. *Phosphorus management strategies for lakes* **1979,** , 235-255.

26. Stow, C.A.; Roessler, C.; Borsuk, M.E.; Bowen, J.D.; Reckhow, K.H. Comparison of estuarine water quality models for total maximum daily load development in Neuse River Estuary. *J. Water Resour. Plann. Manage.* **2003,** *129* (4), 307-314.

27. Scavia, D.; Justic, D.; Bierman, V.J. Reducing hypoxia in the Gulf of Mexico: advice from three models. *Estuaries* **2004,** *27* (3), 419-425.

28. Kirchhoff, C.J.; Lemos, M.C.; Dessai, S. Actionable knowledge for environmental decision making: broadening the usability of climate science. *Annual review of environment and resources* **2013,** *38*.

29. *State of Ohio's Domestic Action Plan*; https://lakeerie.ohio.gov/Portals/0/Ohio%20DAP/DAP%201-1%20FINAL%202018-08-27.pdf.

30. Klenk, N.L.; Meehan, K.; Pinel, S.L.; Mendez, F.; Lima, P.T.; Kammen, D.M. Stakeholders in climate science: Beyond lip service? *Science* **2015,** *350* (6262), 743-744.

31. Garb, Y.; Pulver, S.; VanDeveer, S.D. Scenarios in society, society in scenarios: toward a social scientific analysis of storyline-driven environmental modeling. *Environmental Research Letters* **2008,** *3* (4), 045015.

32. *Conservation Practice Adoption on Cultivated Cropland Acres: Effects on Instream Nutrient and Sediment Dynamics and Delivery in Western Lake Erie Basin, 2003-06 and 2012*; https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcseprd1355824.pdf.

33. Muenich, R.L.; Kalcic, M.; Scavia, D. Evaluating the impact of legacy P and agricultural conservation practices on nutrient loads from the Maumee River Watershed. *Environ. Sci. Technol.* **2016,** *50* (15), 8146-8154.

34. Gildow, M.; Aloysius, N.; Gebremariam, S.; Martin, J. Fertilizer placement and application timing as strategies to reduce phosphorus loading to Lake Erie. *J. Great Lakes Res.* **2016,** *42* (6), 1281-1288.

35. Moriasi, D.N.; Arnold, J.G.; Van Liew, M.W.; Bingner, R.L.; Harmel, R.D.; Veith, T.L. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE* **2007,** *50* (3), 885-900.

36. Malagó, A.; Bouraoui, F.; Vigiak, O.; Grizzetti, B.; Pastori, M. Modelling water and nutrient fluxes in the Danube River Basin with SWAT. *Sci. Total Environ.* **2017,** *603*, 196-218.

37. Arnold, J.G.; Srinivasan, R.; Muttiah, R.S.; Williams, J.R. Large area hydrologic modeling and assessment part I: model development 1. *JAWRA Journal of the American Water Resources Association* **1998,** *34* (1), 73-89.

38. King, K.W.; Williams, M.R.; LaBarge, G.A.; Smith, D.R.; Reutter, J.M.; Duncan, E.W.; Pease, L.A. Addressing agricultural phosphorus loss in artificially drained landscapes with 4R nutrient management practices. *J. Soil Water Conserv.* **2018,** *73* (1), 35-47.

39. Wilson, R.S.; Schlea, D.A.; Boles, C.M.; Redder, T.M. Using models of farmer behavior to inform eutrophication policy in the Great Lakes. *Water Res.* **2018,** *139*, 38-46.

40. Ruddy, B.C.; Lorenz, D.L.; Mueller, D.K. County-level estimates of nutrient inputs to the land surface of the conterminous United States, 1982-2001. **2006,** .

**The cover page for this report was made using a Google Earth image retrieved by the ‘ggmap’ package in R Statistics and combined with NASA MODIS imagery of Lake Erie.

# Appendices

## APPENDIX 1

Table A-1. Maumee River basin model set up details.

| SWAT Modeling | Modeling Decision | Decision Options | Models | | | | |
|---|---|---|---|---|---|---|---|
| | | | OSU | UT | HU | LT | UM |
| Model/Sub-Model Algorithms | Model Version | Rev. 635-modified† | | | | | X |
| | | Other version | 645 | 664 | 645 | 627 | |
| | Tile Drain Routine | Old (SWAT_TDRAIN) | | X | | | |
| | | New (SWAT_HKdc) | X | | | X | X |
| | Water Table Routine | Old | | X | | X | |
| | | New | X | | | | X |
| | In-Stream Processes | On (QUAL2E) | X | X | X | X | X |
| | | On, modified‡ | | | | | |
| | Soil P Model | Old | | X | | X | |
| | | New | X | | | | X |
| | Evapotranspiration Method | Penman-Monteith | X | X | X | | X |
| | | Hargreaves | | | | X | |
| Model Inputs | Land Use Data | NLCD 2001 | | X | | X | |
| | | NLCD 2006 | | | | | X |
| | | CDL 2007-2012 | X | | X | | X |
| | Elevation Model | NED 10m | | | | | |
| | | NED 30m | X | X | X | | |
| | Soils Data | SSURGO | X | X | X | | X |
| | | STATSGO | | | | | |
| | Climate Inputs* | NOAA NCDC - precipitation and temperature | From team | From team | X | | From team |
| | | Simulated solar radiation, wind, relative humidity | | | X | | X |
| | Point Source Inputs* | Measured data from EPA DMR; aggregated to average monthly | From team | From team | X | | |

| SWAT Modeling | Modeling Decision | Decision Options | Models | | | | |
|---|---|---|---|---|---|---|---|
| | | | OSU | UT | HU | LT | UM |
| | | Not included | | | | | |
| Spatial Discretization | HRU Thresholds | LU-Soil-Slope: 0/10/0 | | | | | X |
| | | LU-Soil-Slope: 200 ha/800 ha/800 ha | | | | | |
| | | LU-Soil-Slope: 5/10/0 | 5/20/1 930 | X | | | |
| | | LU-Soil-Slope: 50/25/0 | | | X | | |
| | No. of sub-basins | *Calculation after model setup* | 1482 | 97 | 374 | 203 | 358 |
| | Average HRU Area (ha) | *Calculation after model setup* | 1,130 | 7,700 | 12,677 | | 169 |
| Model Parameterization & Measured Data | Methods for Assessing Model Performance | $R^2$ | X | X | X | X | X |
| | | NSE | X | X | X | X | X |
| | | PBIAS | X | | X | X | X |
| | Variables Model Performance Was Assessed For | Streamflow | X | X | | X | X |
| | | Total Phosphorus | X | X | | X | X |
| | | Dissolved Reactive Phosphorus | X | X | | X | X |
| | | Total Nitrogen | X | X | | X | X |
| | | Nitrate | | | | X | X |
| | | Suspended solids | X | X | | | X |
| | Additional Calibration Checks | Crop Yields | X | X | X | | X |
| | | Tile Flow | X | X | X | X | X |
| | | Field Losses | | | | X | |
| | | Nutrient Loss via Tile Drains | | | | X | X |
| | Calibration and validation time periods | 2010-2015 – calibration | X | X | | | X |
| | | 2005-2009 – validation | X | X | | | X |
| | Spatial Extent of Calibration | At Waterville gage only | | X | X | X | X |
| | | At Waterville, Blanchard and Tiffin | | | | | |
| | | Flow at multiple locations and water quality at Waterville gage | X | | | | |

| SWAT Modeling | Modeling Decision | Decision Options | Models | | | | |
|---|---|---|---|---|---|---|---|
| | | | OSU | UT | HU | LT | UM |
| | | Other – please describe | | | | | |
| | Method to Fill in Missing Data | LOADEST for everything except DRP; Obenour *et al.* (2014) method for DRP | | | | | X |
| | | Model is calibrated only to observed data; missing data not included in calibration | | X | X | | |
| Land Management Operations | Fertilizer Applications | Estimated from county fertilizer sales data from 2002 | | | | | X |
| | | Estimated based on maintenance application from Tri-State Standards | | X | X | X | X |
| | Manure Applications | Aggregated inputs from USDA-ARS NHDPlus SWAT model (*Daggupati et al.* 2015) | | | | | |
| | | Estimated from Ag Census yield and Fertilizer Use data 1990-2010 | | | | | X |
| | | Estimated from county-level livestock count | X | X | | X | X |
| | | Livestock count | | | | | |
| | | Not included | | | | | |
| | Crop Rotations<br>(C = Corn,<br>S = Soybean, W = Winter Wheat,<br>H = Hay)<br>Crop Rotations<br>(C = Corn,<br>S = Soybean,<br>W = Winter Wheat,<br>H = Hay) | CS | X | X | X | X | X |
| | | CSS | | X | X | | X |
| | | CSW | X | X | X | | |
| | | CWS | X | X | X | X | |
| | | CSWCSSW | | | X | | X |
| | | CSWH | X | | | | |
| | | SS | X | | X | X | |
| | | CC | | X | X | X | |

| **SWAT Modeling** | **Modeling Decision** | **Decision Options** | **Models** | | | | |
|---|---|---|---|---|---|---|---|
| | | | **OSU** | **UT** | **HU** | **LT** | **UM** |
| | Tillage | Estimated from CTIC | | | | | X |
| | | Estimated from USDA/OSU Extension consultation | X | | | | |
| | | Estimated from CEAP report | X | X | X | X | X |
| | | Estimated according to crop planted | | X | X | | X |
| | Subsurface drainage | Estimated based on modified RUSLE2 | | | | | |
| | | All Agricultural lands with somewhat poorly, poorly, or very poorly drained soils | X | X | | | X |
| | | C,S,W HRU's with poorly or very poorly drained soils | | | | | |
| | | Agricultural or HAY lands with hydrologic group C or D soils | | | | X | |
| | | Agricultural lands with less than or equal to 3% slope | | | | | |
| | | Agricultural lands with <1% slope | | | X | | |

[*] Data homogenized for this project.

[†] SWAT versions were modified to fix a bug where soluble P was not properly moving through subsurface drains. ‡watqual3 routine is an adaption LimnoTech developed based on White et al. (2014).

Table A-2. Model parameters. Values highlighted in gray indicate the value has changed from the default (DF) in a given model.

| **Parameter** | **File** | **Spatial Level** | **Description** | **Range** | **Final or Calibrated Value** | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | **OSU** | **UT** | **HU** | **LT** | **UM** |
| ***Parameters that turn sub-routines on or off*** | | | | | | | | | |
| ICN | .bsn | Watershed | Daily curve number calculation method: 0-calculate daily CN value as a function of soil moisture; 1-calculate daily CN value as a function of plant evapotranspiration | 0/1 | 0 | DF | 0 | 0 | 0 |
| ICRK | .bsn | Watershed | Crack flow code; 0=no crack flow in soil; 1=crack flow in soil | 0/1 | 0 | DF | DF | 0 | 1 |
| IRTE | .bsn | Watershed | Channel water routing method; 0=variable travel-time; 1=Muskingum | 0/1 | 0 | 0 | 0 | 0 | 0 |
| ISMAX | .bsn | Watershed | Maximum depressional storage flag, 0 = static stmaxd from .sdr | 0/1 | 0 | 0 | 0 | 0 | 1 |
| ITDRN | .bsn | Watershed | Tile drainage equations flag; 1=SWAT_HKdc routine using DRAINMOD; 0=SWAT_TDRAIN method. | 0/1 | 1 | 0 | 1 | 1 | 1 |
| IWQ | .bsn | Watershed | In-stream water quality model: 0-do not simulate nutrient transformations in stream; 1-activate simulation of in-stream nutrient transformations using QUAL2E; 2-watqual2 simulation; 3-watqual3‡. | 0/1 | 1 | 1 | 1 | 1 | 1 |
| IWTDN | .bsn | Watershed | Water table depth algorithms flag | 0/1 | 1 | 0 | 1 | 0 | 1 |

| Parameter | File | Spatial Level | Description | Range | Final or Calibrated Value | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | OSU | UT | HU | LT | UM |
| | | | | | | | | | |
| SOL_P_MODEL$^{\Delta}$ | .bsn | Watershed | Soil phosphorus sub-routine: 0=new model; 1=old model | 0/1 | 1 | 0 | 1 | 1 | 0 |
| ADJ_PKR | .bsn | Watershed | Peak rate adjustment factor | 0.5-1.5 | 1.9 | 1 | 0.724 | 0 | 1 |
| ALPHA_BF | .gw | HRU | Baseflow recession constant | 0.1-0.99 | 0.048-0.6 | 0.9964 | 0.299 | 0.254 | 0.9 |
| ANION_<br>EXCL | .sol | HRU | Fraction of soil pore space from which anions are excluded | 0-1 | 0.5 | DF | 0.5 | 0.5 | 0.33 |
| BC1 | .swq | Subbasin | Biological oxidation rate of NH4 to NO2 in the reach at 20° (1/day) | 0.1-1 | 0.925 | 0.55 | DF | 0.36 | 0.1 |
| BC2 | .swq | Subbasin | Rate constant for biological oxidation of NO2 to NO3 in the reach at 20° C (1/day) | 0.2-2 | 1.926 | | | 1.1 | 0.2 |
| BC3 | .swq | Subbasin | Hydrolysis rate of organic N to NH4 in the reach at 20° (1/day) | 0.2-0.4 | 0.31 | 0.21 | DF | 0.2 | 0.02 |
| BC4 | .swq | Subbasin | Mineralization rate of organic P to DRP in the reach at 20° (1/day) | 0.01-0.7 | 0.012 | 0.01 | 0.005 | 0.01 | 0.01 |
| BIOMIX | .mgt | HRU | Biological mixing efficiency | NA | 0.75 | 0.2 | 1.142 | 0.2-0.6 | 0.25 |
| CANMX | .hru | HRU | Maximum canopy storage (mm H2O) | NA | DF | DF | 1.055 | 5.732 | DF |
| CDN | .bsn | Watershed | Rate coefficient for denitrification | 0-3 | 0.017 | 1.4 | 1.4 | 0.3 | 1.4 |
| CH_COV1 | .rte | Subbasin | Channel cover factor 1 | 0-1 | 0 | DF | 0.22 | 0.048 | 0.5 |
| CH_COV2 | .rte | Subbasin | Channel cover factor 2 | 0-1 | 0 | DF | 0.354 | 0.048 | 0.5 |
| CH_K1 | .sub | Subbasin | Effective hydraulic conductivity (mm/hr) | 0.025-25 | DF | DF | 3.534 | DF | DF |

| Parameter | File | Spatial Level | Description | Range | Final or Calibrated Value | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | OSU | UT | HU | LT | UM |
| CH_K2 | .rte | Subbasin | Effective hydraulic conductivity of channel (mm/hr) | 0.025-25 | DF | DF | 23.52 | 0.417 | DF |
| CH_N1 | .sub | Subbasin | Manning's roughness for tributary channels | 0-0.15 | 0.014 | 0.014 | 0.131 | DF | 0.02 |
| CH_N2 | .rte | Subbasin | Manning's roughness for the main channel | 0-0.15 | 0.06 | 0.014 | 0.147 | 0.057 | 0.035 |
| CN2 | .mgt | HRU | Initial SCS moisture condition II curve number | 0.75-1.25[†] | varies | 35-98 | 49.74 – 96.98 | 30-95 | DF |
| CNOP | .mgt | HRU | SCS runoff curve number for moisture condition II | NA | DF | DF | DF | 75-89 | DF |
| DDRAIN | .mgt | HRU | Depth to subsurface tile drain (mm) | 0-6000 | 1000* | 0-2000 | 915* | 1000* | 1000* |
| DEP_IMP | .hru | HRU | Depth to the impervious layer in the soil (mm) | 0-6000 | 2300* | 0-6000 | 1294* | 2500-3500 for drained* | 1500* |
| DRAIN_CO | .sdr | HRU | Daily drainage coefficient (mm/day) | Oct-51 | 35 | DF | DF | 12.7 | 20 |
| EPCO | .bsn | Watershed | Plant uptake compensation factor. | 0.01-1.0 | 0.95-1.0 | 1 | 1 | 0.6381 | 1 |
| ERORGN | .hru | HRU | Nitrogen enrichment ratio for loading with sediment, 0 allows model to calculate value | NA | DF | 1.174 | DF | 2 | DF |
| ERORGP | .hru | HRU | Phosphorus enrichment ratio for loading with sediment, 0 allows model to calculate value | NA | DF | 1.25 | DF | 2 | DF |
| ESCO | .bsn,<br>.hru | Watershed<br>HRU | Soil evaporation compensation factor | 0.01-1 | 0.97$^{\text{hru}}$ | 0.95 | 0.997$^{\text{bsn}}$ | 1 | 0.95$^{\text{bsn}}$ |
| GDRAIN | .mgt | HRU | Drain tile lag time (hours) | NA | NA | 24 | 2 | 96 | NA |
| GW_DELAY | .gw | HRU | Delay time for aquifer recharge (days) | NA | 31-Mar | DF | 5.177 | 31 | DF |

| Parameter | File | Spatial Level | Description | Range | Final or Calibrated Value | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | OSU | UT | HU | LT | UM |
| GWQMN | .gw | HRU | Threshold water level in shallow aquifer for base flow (mm H2O) | NA | 780-1000 | DF | 817.66 | 447.58 | DF |
| GW_REVAP | .gw | HRU | Revap coefficient | 0.02-2 | 0.02 | 0.2-2 | 0.055 | 0.02 | 0.07 |
| HRU_SLP | .hru | HRU | Average slope steepness (m/m) | 0.75-1.25† | DF | DF | DF† | varies by HRU, max of 0.079 | DF |
| IFLOD1R | .res | Subbasin | Beginning month of non-flood season | 12-Jan | DF | DF | DF | 1 or 12 | DF |
| IFLOD2R | .res | Subbasin | Ending month of non-flood season | 12-Jan | DF | DF | DF | 1 | DF |
| LATKSATF | .sdr | HRU | Lateral soil hydraulic conductivity in tile-drained fields as multiple of original soil conductivity value | 0.01-4 | 0.54 | DF | 0.994 | 2 or 4 | 1 |
| NDTARGR | .res | Subbasin | Number of days to reach target storage from current reservoir storage | NA | DF | DF | DF | 1 or 5 | DF |
| NPERCO | .bsn | Watershed | Nitrate percolation coefficient | 0.01-1 | 0.36 | 0.2 | 0.284 | 0.5 | 0.9 |
| OVN | .hru | HRU | Manning's "n" value for overland flow | 0.008-0.5 | 0.029 | X | 1.227 | 0.1 to 0.3 | 0.1-0.2 |
| PHOSKD | .bsn | Watershed | Phosphorus soil partitioning coefficient ($m^3$/Mg) | 80-350 | 181 | 204.5 | 173.8 | 175 | 175 |
| PPERCO | .bsn | Watershed | Phosphorus percolation coefficient ($m^3$/Mg) | 10-17.5 | 10 | 10.94 | 11.637 | 5 | 10 |
| PSP | .bsn | Watershed | Phosphorus availability index | 0.2-0.6 | 0.4 | 0.425 | 0.62 | 0.1 | 0.4 |
| R2ADJ | .hru | HRU | Curve number adjustment for increasing infiltration in non-draining soils | 0-3 | 1 | 1 | 0.907 | 1.15 to 3 | 1 |
| RE | .sdr | HRU | Effective radius of drains (mm) | Mar-40 | 30 | DF | 37.9 | 10 | 20 |

| Parameter | File | Spatial Level | Description | Range | Final or Calibrated Value | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | OSU | UT | HU | LT | UM |
| REVAPMN | .gw | HRU | Threshold water level in shallow aquifer for revap (mm $H_2O$) | NA | 116-750 | DF | 947 | 388.62 | DF |
| RS1 | .gw | HRU | Local algal settling rate in the reach at 20°C (m/day) | 0.015-1.82 | DF | DF | DF | 1 | 1 |
| RS2 | .swq | Subbasin | Benthic source rate for DRP in the reach at 20° (mg P/$m^2$-d) | NA | 0.03 | DF | x1.22 | 0.05 | 0.01 |
| RS3 | .swq | Subbasin | Benthic source rate for ammonium in the reach at 20° (mgNH4-N/m2/d) | NA | 0.46 | DF | x0.927 | 0.5 | 1 |
| RS4 | .swq | Subbasin | Organic N settling rate in the reach at 20° (1/day) | 0.001-0.1 | 0.003 | DF | DF | 0.01 | 0.001 |
| RS5 | .swq | Subbasin | Local settling rate for organic phosphorus mineralization at 20° ($day^{-1}$) | 0.001-0.1 | 0.1 | DF | x1.071 | 0.01 | 0.05 |
| SDNCO | .bsn | Watershed | Threshold value of nutrient cycling water factor for denitrification to occur | 0.75-1.4 | 0.97 | 1.1 | 1.287 | 1 | 1.1 |
| SDRAIN | .sdr | HRU | Tile drain spacing (mm) | 7,600-30,000 | 10000* | | 21165 | 13720 | 10000* |
| SFTMP | .bsn | Watershed | Mean air temperature at which precipitation is equally likely to be rain as snow/freezing rain (°C) | -10 | -2 | 1 | -0.7 | 1 | -2 |
| SHALLST | .gw | HRU | Initial depth of water in the shallow aquifer (mm H2O) | NA | 1000 | | DF | 500 | DF |
| SLSUBSN | .hru | HRU | Average slope length | 0.75-1.25 | DF | DF | x1.224 | | DF |
| SMFMN | .bsn | Watershed | Minimum snow melt factor (mm $H_2O$/day-°C) | 1.4-6.9 | 2 | 4.5 | 4.1 | 3 | 2 |

| Parameter | File | Spatial Level | Description | Range | Final or Calibrated Value | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | OSU | UT | HU | LT | UM |
| SMFMX | .bsn | Watershed | Maximum snow melt factor (mm $H_2O$/day-°C) | 1.4-6.9 | 2 | 4.5 | 6.6 | 4-Jan | 2 |
| SMTMP | .bsn | Watershed | Threshold temperature for snowmelt (°C) | -10 | -2 | 0.5 | 2.08 | 0.5 | -2 |
| SOL_AWC | .sol | HRU | Available water capacity | 0.75-1.25 | varis – calib. parameter | DF | x0.854 | DF | DF |
| SOL_CRK | .sol | HRU | Potential crack volume for soil profile | 0-1 | DF | DF | 0.142 | DF | 0.42 |
| SOL_K | .sol | HRU | Saturated hydraulic conductivity (mm/hr) | 0.75-1.25 | varis – calib. parameter | DF | x0.922 | DF | DF |
| SOL_ORGP | .chm | HRU | Initial humic organic phosphorus in soil layer (mg/kg or ppm) | 50-250 | DF | DF | 202 | DF | DF |
| SOL_SOLP | .chm | HRU | Initial labile P in the soil layer (mg labile P/kg soil) | 5-100 | 0.5 | DF | 0.7 | DF | 1 |
| SPCON | .bsn | Watershed | Parameter drives the maximum concentration of sediment the river can route | 0.0001-0.01 | 0.0026 | 8.00E-04 | 2.60E-04 | 0.004 | 2.22E-04 |
| SPEXP | .bsn | Watershed | Exponent parameter for calculating sediment reentrained in channel sediment routing | 1-2 | 1.425 | DF | DF | 1 | 1 |
| SURLAG | .bsn | Watershed | Surface runoff lag coefficient | NA | 1 | 4 | 1.007 | 2.8723 | 1 |
| TDRAIN | .mgt | HRU | Time to drain soil to field capacity (hours) | NA | NA | 48 | 36 | | NA |
| TIMP | .bsn | Watershed | Snow pack temperature lag | 0.01-1 | 0.05 | 1 | 0.327 | 0.06 | 0.05 |
| USLE_C | crop.dat | By land-use | Minimum value for the cover and management factor for the land cover | 0.75-1.25 | DF | DF | x1.055 | DF | DF |

| Parameter | File | Spatial Level | Description | Range | Final or Calibrated Value | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | OSU | UT | HU | LT | UM |
| USLE_K | .sol | HRU | USLE soil erodibility factor (0.013 metric ton $m^2$-hr/$m^3$-metric ton cm) | 0.75-1.25 | varis – calib. parameter | DF | x1.118 | DF | DF |
| USLE_P | .mgt | HRU | USLE support practice factor | 0.50-1.25 | varis – calib. parameter | 0.16-1.6 | DF | 1 | DF |
| VCRIT | .bsn | Watershed | Critical velocity at which a river will resuspend sediments | NA | 5 | 5 | 5 | 0 | 1 |

[‡] watqual3 routine is an adaption LimnoTech developed based on White et al. (2014).

[Δ] SWAT 2012 revision 635 indicate in basins.bsn that 1 is the new soil phosphorus model; however, examination of the source code followed by confirmation from Nancy Sammons (in a post to the SWAT-user group on 2/26/2014) confirms that setting this parameter equal to 0 will run the new soil phosphorus sub-routine.

Table A-3. Watershed management decisions based on guidelines provided to the modeling teams.

| No | Input type | Model setup guidance | Decision | | | | |
|---|---|---|---|---|---|---|---|
| | | | OSU | UT | HU | LT | UM |
| 1 | Phosphorus fertilizer application | Phosphorus (P) fertilizer is incorporated in approximately 60% of the cropland, and the rest is broadcast application. The CEAP report informs that in 2012 that 40% of acres had all broadcast applications with no incorporation, and 60% of acres had all applications incorporated. | Subsurface placement on 35% of cropland | Ensured that a tillage operation immediately followed MAP application for 60% of cropland. | Full subsurface application: 43.6%<br>Combined subsurface and broadcast: 53.6%<br>Purely Broadcast with no incorporation: 2.8% | MASWAT Cal015 was modified to change all FRT_SURFACE values to 0.10. Then, this modified management file was run through the R script and 40% of the land area in AGRR was changed to 0.75. The R script was applied to both P and N fertilizers for consistency. | 57% of acres had all P fertilizer applications incorporated within 3 days; 22% had all P fertilizer applications broadcast without incorporation; 21% had a mixture of broadcast with incorporation and without. |
| 2 | Cover crop | The CEAP report says "fewer than 6 percent of acres were managed with cover crops" in 2012, yet the Wilson report [Burnett et al., 2015] suggests closer to 10% with increasing rates the past few years. Cover crops are applied in the fall and should not include winter wheat. | Cover crop (rye) is planted in 8.4% of the cropland, and only in corn-soybean rotations. | Cover crop (rye) is planted in 10% of total, corn-soy rotations | 6% of HRUs | In the R script utilized, Pchange was set to 7.5%. Based on HRU size and random selection, 7.5% of the ag land was changed to include cover crops. The cover crop chosen was a RYE plant which was planted 7 days after the harvest of either a CORN or SOYBEAN crop. WHEAT was excluded. Heat units to maturity was set | Cover crop (rye) is planted in 8.4% of cropland, in every winter of a CSS rotation, in which P fertilizers are fully incorporated |

| No | Input type | Model setup guidance | Decision | | | | |
|---|---|---|---|---|---|---|---|
| | | | OSU | UT | HU | LT | UM |
| | | | | | | as 1540. All cover crops were killed using operation 8 on April 15th. | |
| 3 | Vegetative filter strip | 30% of the cropland has filter strips. | 29% of the cropland (corn, soybean, winter wheat and hay pasture) | Applied to 32% of croplands | 30% of HRUs (still need to calculate) | NR | 34% of cropland received a medium-quality filter strip. Rotations include CS and CSS (P fertilizers fully incorporated), and two CSWCSSW rotations (with P fertilizers partially or not at all incorporated). |
| 4 | Manure application | The CEAP report informs that manure is applied in 9% of the cropland, whereas, the OSU farmer survey reports 14%. Modeling teams were provided with application rates by county, livestock numbers and references to estimate manure production. | Varying levels of application by county. Nearly 14% of the cropland receives manure. We estimated dairy-equivalent manure production based on livestock count at county level and applied all manure to HRUs within that county. We estimated elemental N and P amount in manure applied and reduced that amount in mineral fertilizer applications (in | Approximately 14% of the fields had manure applied. Amount was based on county livestock counts and type, and evenly distributed over 14% of the county by area. | Application rates by county was implemented. Original N & P app rates were maintained as sum of both manure and inorganic. | For manure, the raw NuGIS data was used rather than the estimates for manure P provided by OSU. Data was trimmed down to only years 2010 to 2012. The recovered manure estimates were used and converted to elemental P from P2O5. The ‘Farm_TonsP’ was converted to elemental P from P2O5 and used to estimate mineral fertilizer. | Varying levels of application by county. *All* cropland within a country received manure from livestock produced in that county. This is an assumption we intend to improve soon. We estimated the manure generated in each county from the Ag Census livestock numbers and applied the SWAT default manure for dairy, beef, swine, layer, and broilers. |

| No | Input type | Model setup guidance | Decision | | | | |
|---|---|---|---|---|---|---|---|
| | | | OSU | UT | HU | LT | UM |
| | | | MAP – mono ammonium phosphate). | | | Another R script was used to add the manure to the cropland HRUs in the HABRI model (cal0030, with the fertilizer updates). This script cycled through the mgt2 table of the updated model. The first loop was based on the county. Every HRU was tagged with the county it resided in (this was based on subbasin). Total county area was calculated by summing the HRUs. The script then noted the total amount of annual fertilizer which should be applied and fraction of the county crop area which should receive manure. If the county fraction was zero, no HRUs were selected and no manure was applied in that county. This gave an estimated land area to which manure should be applied. Next the script randomized the county HRUs and selected enough HRUs to meet or exceed the area target. Phosphorus was applied using layer manure, which has a P fraction of 0.006 and an N fraction of 0.013. | |

| No | Input type | Model setup guidance | Decision | | | | |
|---|---|---|---|---|---|---|---|
| | | | OSU | UT | HU | LT | UM |
| 5 | Subsurface drainage | 70-78% of the cropland has subsurface drainage. Our estimate is based on total cropland and subsurface drainage extent reported in the CEAP report Table 1.1 and chapter 3 (4,861,000 acres of cropland, (3,400,000-3,800,000 acres treated with subsurface drainage). These values are for all Western Lake Erie watersheds. | 75% of the cropland has subsurface drainage installed. | 77% of the cropland has subsurface drainage | < 3% slope have drainage. | 76% has drainage | 71.5% of cropland has subsurface drainage. |
| 6 | Tillage | The CEAP report (Figure 2.1) informs that 20-30% of cropland is managed in continuous no-tillage and 25-35% of cropland is managed in seasonal no-tillage. | No-till is practiced in 37% of the cropland. | NR | 63% Rotational Till<br>36.5% Pure No till<br>0.5% Conventional Till | NR | Continuous no-till is practiced in 22% of cropland (in one CSS rotation and two CSWCSSW rotations);<br>Seasonal no-till is practiced in 21% of cropland (in one CS rotation and one CSWCSSW rotation) |
| 7 | Point sources | Modeling teams were provided with point source information. | All point sources are included in the model. Point source data was compiled by UM. | All point sources included from UM compilation | NR | Point source data included which was sent via Box account | All point sources are included in the model. Point source data was compiled by UM. |

*NR were values not reported by the modeling team.

# APPENDIX 2

For this multi-model project, in addition to the point source, we also developed an approach to account for the nutrient loads from combined sewer overflows (CSOs) driven by the precipitation and the stormwater. The point source input files for this project thus include both point source and CSO nutrient loads.

Like the previous multi-model project, to prepare the point source discharge data for model calibration, we downloaded all the point source facility discharge data in the Maumee River watershed from October 2008 to December 2015 from the Environmental Protection Agency (EPA) Discharge Monitoring Report (DMR) Pollutant Loading Tool (http://cfpub.epa.gov/dmr/ez_search.cfm; now the website has been upgraded to Water Pollution Search, https://echo.epa.gov/trends/loading-tool/water-pollution-search). The discharge data contain the average monthly flow and nutrient measurement for each facility based on data submitted by the National Pollutant Discharge Elimination System (NPDES) permit holders.

We calculated the monthly loads of total suspended solids, total nitrate and nitrite, total ammonia, total Kjeldahl nitrogen, and total phosphorus. After that, based on the instruction of monthly records listed in the SWAT documentation, we calculated the average daily loading of flow (FLOMON), sediment (SEDMON), organic nitrogen (ORGNMON), organic phosphorus (ORGPMON), nitrate (NO3MON), ammonia (NH3MON), nitrite (NO2MON), mineral phosphorus (MINPMON) of each month. Organic phosphorus was calculated as total phosphorus multiplied by 0.53, while mineral phosphorus was calculated as total phosphorus multiplied by 0.47. The ratio of mineral P to organic P based on discharge measurements from the Toledo wastewater treatment plant based on personal communication with Dr. Nate Bosch on July 16, 2015. If there were missing values from January 2005 to December 2015 for one facility, we calculated the average load from the same calendar month to impute the values. If no data were available from the same calendar month, we used the average load from the entire period. Finally, if no data are available from the entire period, we assumed the load from this facility is zero.

The list of CSO facility was downloaded from EPA's website (https://www.epa.gov/npdes/combined-sewer-overflows-great-lakes-basin). Based on the list, the monthly CSO discharge data were also downloaded from EPA DRM Pollutant Loading Tool. For each facility, we developed a linear regression model using the monthly precipitation data from the nearest station as the explanatory variable and monthly CSO discharge as the response variable. If the Coefficient of Determination (R-squared) of the model is larger than or equal to 0.5, the linear regression model was applied to predict missing CSO discharge in the dataset. Otherwise, if R-squared is smaller than 0.5, we used the same approach as the point source by using the average amount to input missing values. After CSO discharge was calculated or predicted for each facility, the monthly CSO nutrient loads were calculated by multiplying the CSO discharge with estimated nutrient concentrations from Brombach et al. (2005). The calculated CSO loads were combined with the point source load data to prepare the final input data to the SWAT models.

## APPENDIX 3

In the previous multi-modeling project described by Scavia et al. (2017)[14] only two of the five modeling groups included manure applications within their models. In the current project all five modeling groups included manure applications; however, the amount of manure nutrients and spatial applications varied by modeling group. The data sources that the modeling groups used to calculate the amount of manure nutrients generated within the watershed include the 2012 Agricultural Census in conjunction with methods described by Ruddy et al. (2006)[39] and the Nutrient Use Geographic Information System (NuGIS).

The percentage of agricultural cropland receiving manure varied between 9% and 14% among the five models. Further differences among the five models include the type of manure applied (i.e., solely layer manure or a combination of various manure types), county-level manure application rates, and the fraction of agricultural cropland HRUs receiving manure within each county.

## APPENDIX 4

Table A-4. Modeled water budgets and crop yields compared to edge-of-field data.37

| Watershed Hydrology (all are mm/year) and Crop Yields (all are bushels/acre) | | | | | | |
|---|---|---|---|---|---|---|
| | **Observed** | **OSU** | **UT** | **HU** | **LT** | **UM** |
| Precipitation | | | | | | |
| Total runoff | 362±100* | 355 | 366 | 392 | 403 | 344 |
| Surface | | 222 | 204 | 187 | 214 | 111 |
| Lateral | | 7 | 3 | 27 | 5 | 2 |
| Subsurface (tile)** | 260-515*** | 165 | 117 | 208 | 182 | 267 |
| Groundwater | | 15 | 85 | 20 | 61 | 94 |
| Evapotranspiration | | 613 | 605 | 583 | 566 | 565 |
| | | | | | | |
| Corn Yield | 153±21 | 135 | 160 | 114 | 128 | 126 |
| Soybean Yield | 46±4 | 36 | 58 | 41 | 42 | 37 |
| Wheat Yield | 69±5 | 64 | 67 | 65 | 47 | 71 |

* Data from National Center for Water Quality Research at Heidelberg University

** Results show area-weighted mean and includes results only from HRUs with tile drains

*** Pease, L. 2016. Characterization of Agricultural Subsurface Drainage Water Quality and Controlled Drainage in the Western Lake Erie Basin. Thesis. The Ohio State University

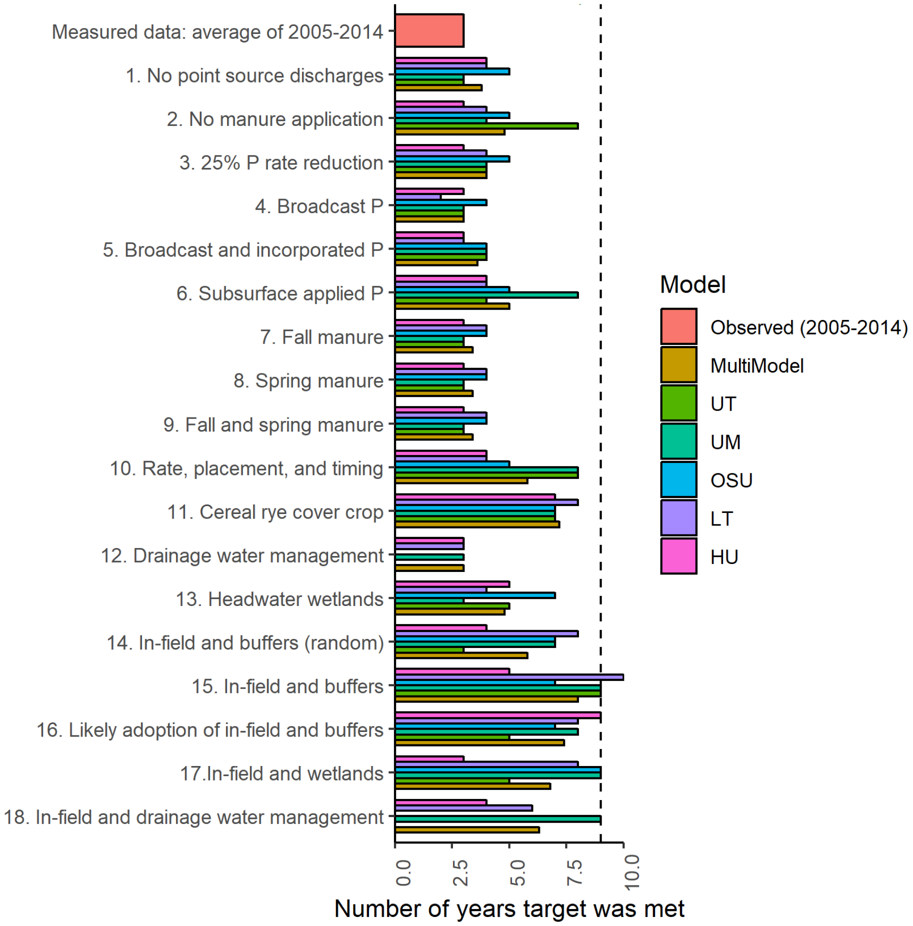

Figure A-1. The individual and multi-model results for each scenario in terms of the years that the March-July TP loading target was met. The dashed line represents the 9-out-of-10 year goal.

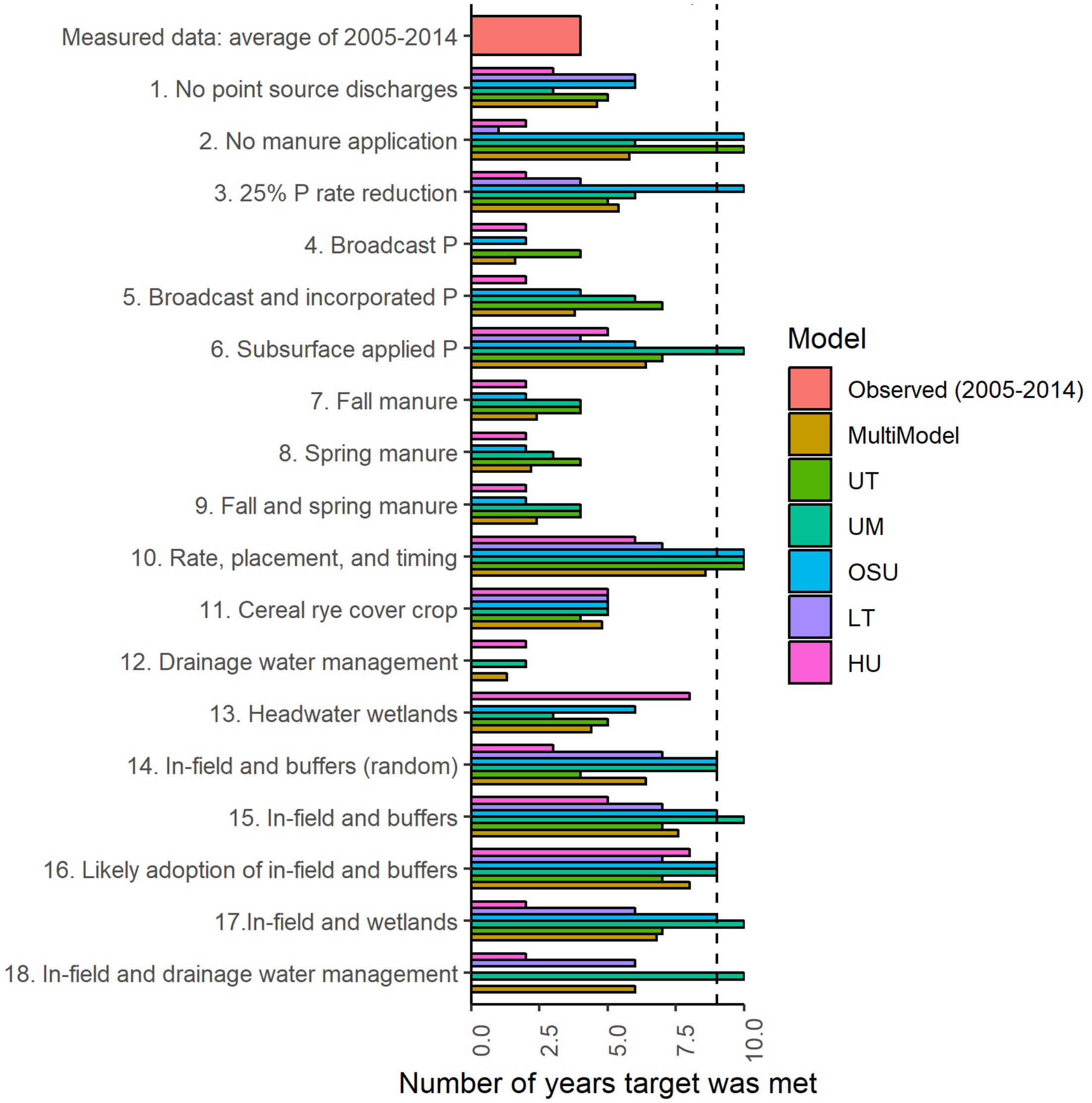

Figure A-2. The individual and multi-model results for each scenario in terms of the years that the March-July DRP loading target was met. The dashed line represents the 9-out-of-10 year goal.

Table A-5. The multi-model average for number of years in which the March-July TP/DRP loading targets were met for each of the scenarios.

| Scenario | TP | DRP |
|---|---|---|
| Observed (2005-2014) | 3 | 3 |
| No point source discharges | 3.8 | 3.8 |
| No manure application | 4.8 | 4.6 |
| 25% P Rate Reduction | 4 | 3.8 |
| Broadcast P | 3 | 2.8 |
| Broadcast and incorporated P | 3.6 | 3.6 |
| Subsurface applied P | 5 | 5 |
| Fall Manure | 3.4 | 3.2 |
| Spring Manure | 3.4 | 2.8 |
| Fall and Spring Manure | 3.4 | 3 |
| Rate, placement & timing | 5.8 | 6 |
| Cereal rye cover crop | 7.2 | 3.6 |
| Drainage water management | 3 | 2.3 |
| Headwater wetlands | 4.8 | 3.8 |
| In-field and buffers (random) | 5.8 | 4 |
| In-field and buffers | 8 | 5.4 |
| Likely adoption of in-field + buffers | 7.4 | 4.8 |
| In-field and wetlands | 6.8 | 5.2 |
| In-field and drainage water management | 6.3 | 5 |

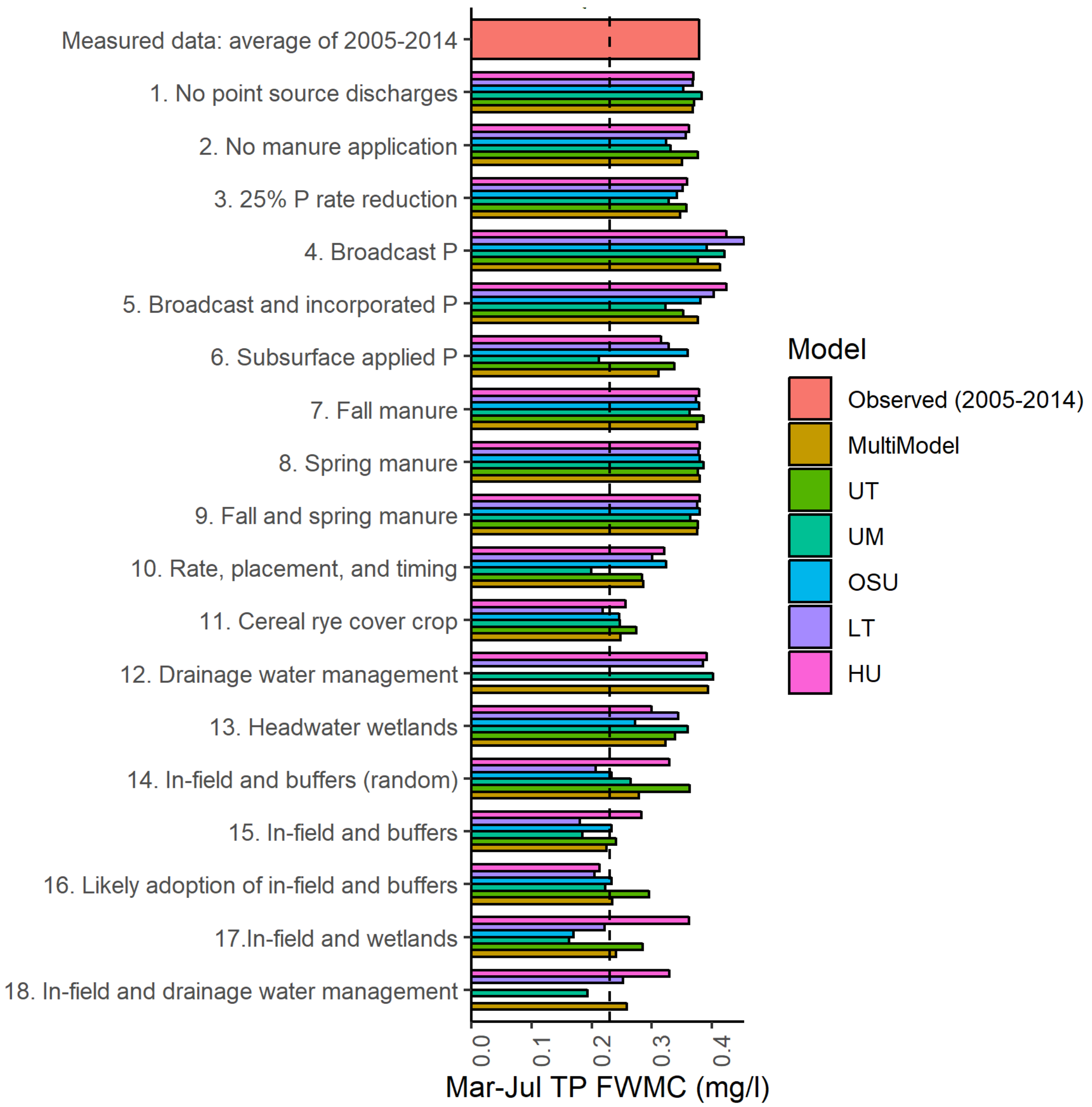

Figure A-3. The individual and multi-model results for each scenario in terms of average TP flow-weighted mean concentrations. The dashed line represents the GLWQA target.

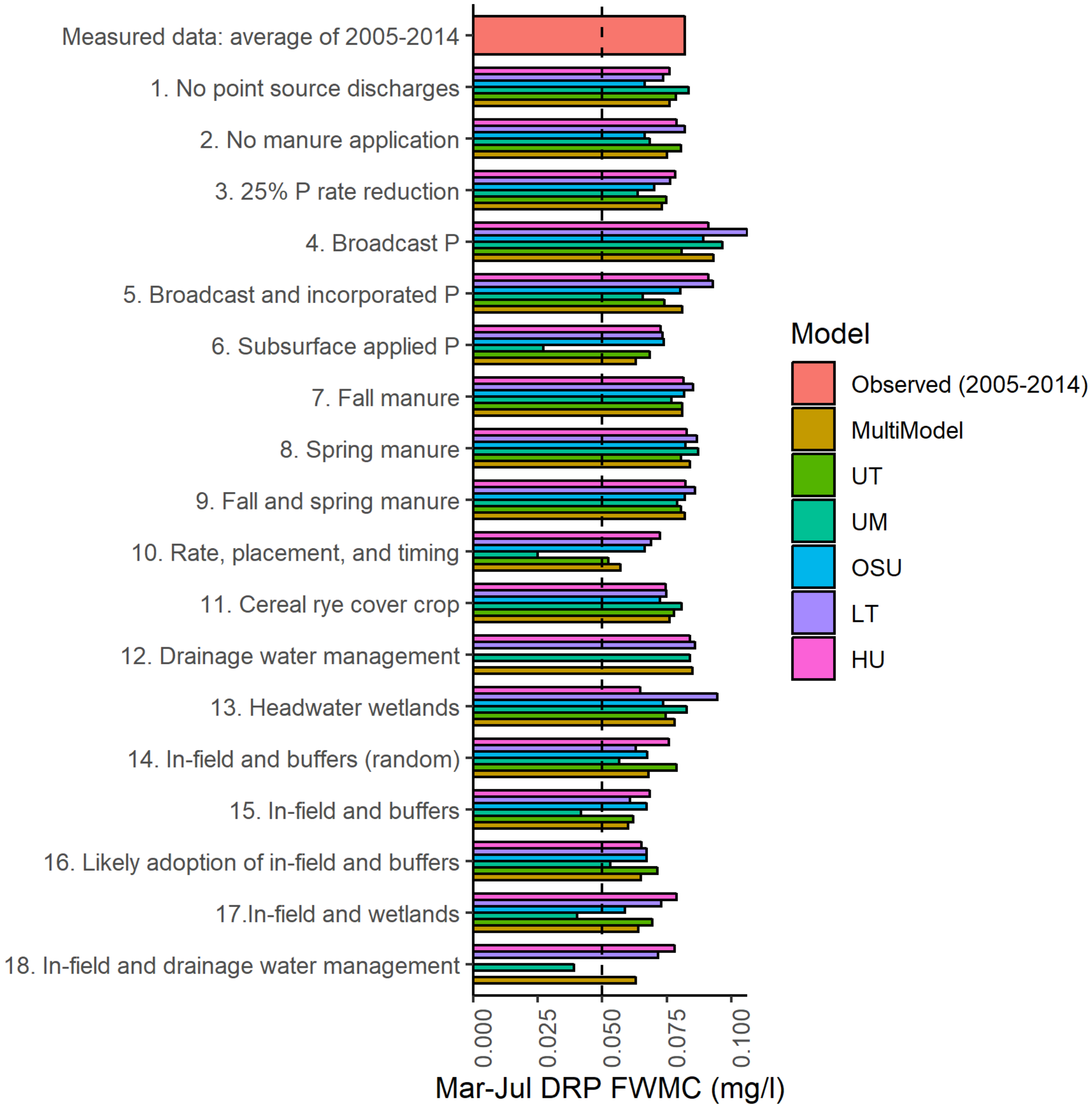

Figure A-4.. The individual and multi-model results for each scenario in terms of average DRP flow-weighted mean concentrations. The dashed line represents the GLWQA target.

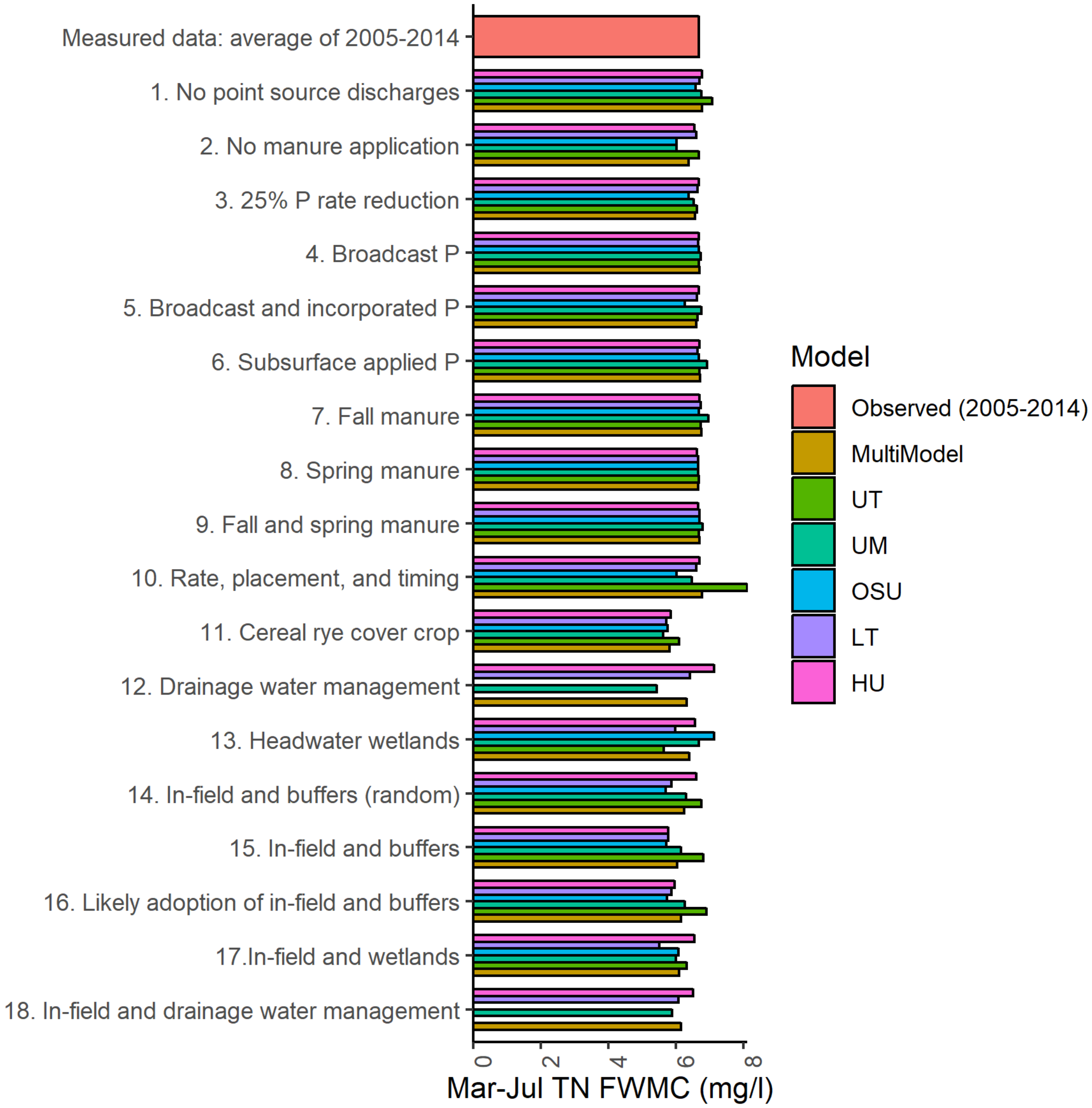

Figure A-5. The individual and multi-model results for each scenario in terms of average TN flow-weighted mean concentrations.

Table A-6. The multi-model average FWMC of TP, DRP, and TN for each of the scenarios.

| Scenario | TP | DRP | TN |
|---|---|---|---|
| Observed (2005-2014) | 0.379 | 0.082 | 6.68 |
| No point source discharges | 0.368 | 0.076 | 6.776 |
| No manure application | 0.35 | 0.075 | 6.369 |
| 25% P Rate Reduction | 0.347 | 0.073 | 6.566 |
| Broadcast P | 0.413 | 0.093 | 6.688 |
| Broadcast and incorporated P | 0.377 | 0.081 | 6.592 |
| Subsurface applied P | 0.311 | 0.063 | 6.72 |
| Fall Manure | 0.376 | 0.081 | 6.76 |
| Spring Manure | 0.38 | 0.084 | 6.654 |
| Fall and Spring Manure | 0.375 | 0.082 | 6.701 |
| Rate, placement & timing | 0.286 | 0.057 | 6.777 |
| Cereal rye cover crop | 0.248 | 0.076 | 5.805 |
| Drainage water management | 0.393 | 0.085 | 6.324 |
| Headwater wetlands | 0.323 | 0.078 | 6.398 |
| In-field and buffers (random) | 0.279 | 0.068 | 6.239 |
| In-field and buffers | 0.225 | 0.06 | 6.044 |
| Likely adoption of in-field + buffers | 0.234 | 0.065 | 6.142 |
| In-field and wetlands | 0.24 | 0.064 | 6.09 |
| In-field and drainage water management | 0.258 | 0.063 | 6.155 |