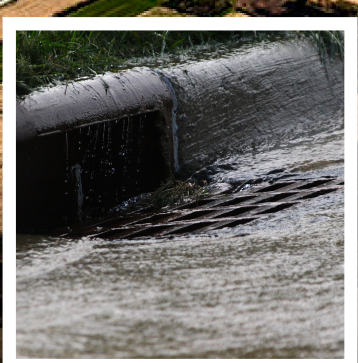
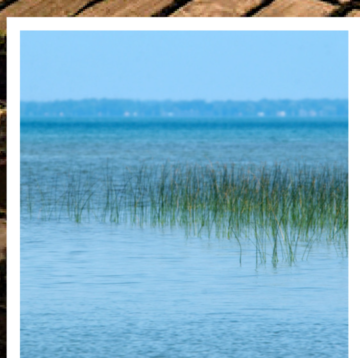
Watershed Assessment of Detroit River Phosphorus Loads to Lake Erie

FINAL REPORT | MAY 2019





Fred A. and Barbara M.
Erb Family Foundation

WATER CENTER
UNIVERSITY OF MICHIGAN

WATERSHED ASSESSMENT OF DETROIT RIVER PHOSPHORUS LOADS TO LAKE ERIE
Final Report | May 2019

About this report:

This report summarizes key findings from a three-year research project funded by the Fred A. and Barbara M. Erb Family Foundation. The project was managed by the University of Michigan Water Center, Graham Sustainability Institute. Project results and methods are described in detail in journal articles and in report supplemental information, all of which can be accessed through the project webpage: myumi.ch/detroit-river

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Suggested citation: Scavia, D., S. Bocaniov, A. Dagnew, Y. Hu, B. Kerkez, C. Long, R. Muenich, J. Read, L. Vaccaro and Y. Wang. 2019. Watershed Assessment of Detroit River Phosphorus Loads to Lake Erie. Final project report produced by the University of Michigan Water Center. Available at: myumi.ch/detroit-river

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Cover photos by: Zach Haslick, Aerial Associates; *Inset pictures*: Robert Lawton *(left)*, Michigan Sea Grant *(center and right)*

EXECUTIVE SUMMARY

1. PROJECT INTRODUCTION

The rivers flowing into Lake Erie carry phosphorus and other nutrients that can lead to harmful algal blooms in its western basin and hypoxic (low oxygen levels) conditions in its central basin. Despite nutrient management efforts, algal blooms and hypoxia that impact drinking water, tourism, swimming and fishing have become more extensive in recent years. In 2012, the US and Canada signed a revised *Great Lakes Water Quality Agreement* which, in 2016, led to the adoption of new phosphorus loading targets and the development of action plans to meet those targets. The plans were released in 2018.

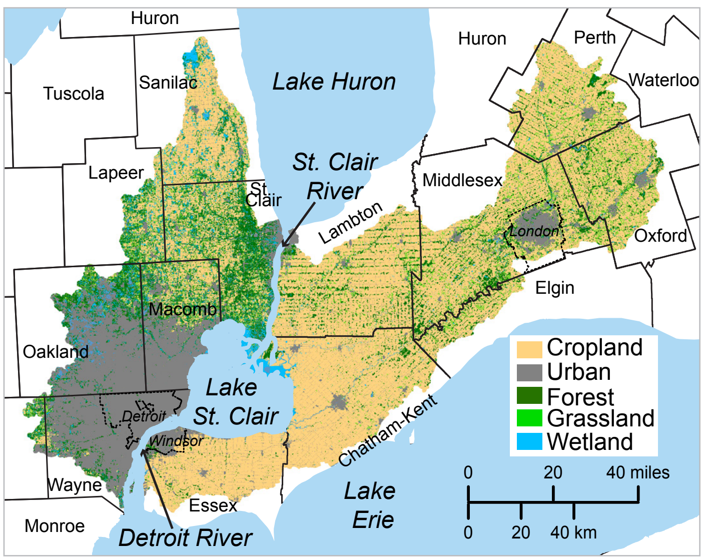

Figure A. ***Project study area.*** This map shows the land use in the St. Clair-Detroit River System watershed. The watershed contains both highly urbanized areas, including the city of Detroit and its large metro area, and extensive agricultural areas, including some of Canada's most productive cropland.

The Detroit River provides approximately 80% of the flow and 25% of the phosphorus entering Lake Erie; however, the sources of this load have been somewhat uncertain. In 2016, the Erb Family Foundation provided support to a project team based at the University of Michigan to characterize sources and evaluate management options for the St. Clair-Detroit River System watershed (Figure A). The team developed four models to simulate the dynamics of this complex, binational watershed that includes extensive urban and agricultural environments as well as the large, shallow, productive Lake St. Clair, which receives and processes inputs from upstream of the Detroit River. A diverse project advisory group provided feedback on the policy context, planned research approach, and resulting products.

2. OVERVIEW OF PHOSPHORUS SOURCES

To characterize sources of phosphorus, we compiled and analyzed data from US and Canadian water quality monitoring programs and point sources between 1998 and 2016, and estimated loads from tributaries to the St. Clair River, Lake St. Clair, and the Detroit River. Our calculations show that Detroit River phosphorus loads to Lake Erie declined by 37% since 1998 and by 19% since 2008.

We found that phosphorus from Lake Huron makes up about half of the load that the Detroit River delivers to Lake Erie, which is substantially higher than most prior estimates. Further analysis of satellite imagery suggests that storms are causing shoreline erosion and resuspension of nearshore Lake Huron bottom sediments, and this sediment is getting transported into the St. Clair River episodically, evading most current monitoring programs.

After Lake Huron, the largest contributors of phosphorus to the Detroit River are the regional Water Resources Recovery Facility in Detroit, and the Thames River in Ontario, which receives runoff from its highly productive agricultural watershed (Figure B). Excluding Lake Huron, the watershed contributions of phosphorus to the Detroit River can be broken down as follows: point sources from Michigan (43% of watershed inputs), non-point sources from Ontario (31%), nonpoint sources from Michigan (19%), point sources from Ontario (7%). This analysis provides the backdrop for assessing potential approaches to reduce the Detroit River's phosphorus contribution to Lake Erie.

3. NUTRIENT PROCESSING IN LAKE ST. CLAIR

Lake St. Clair receives water and phosphorus from the upper Great Lakes via the St. Clair River, many tributaries, including the Clinton, Thames, and Sydenham rivers, and point sources that discharge directly into the lake. To better understand how this lake processes phosphorus, we analyzed long-term

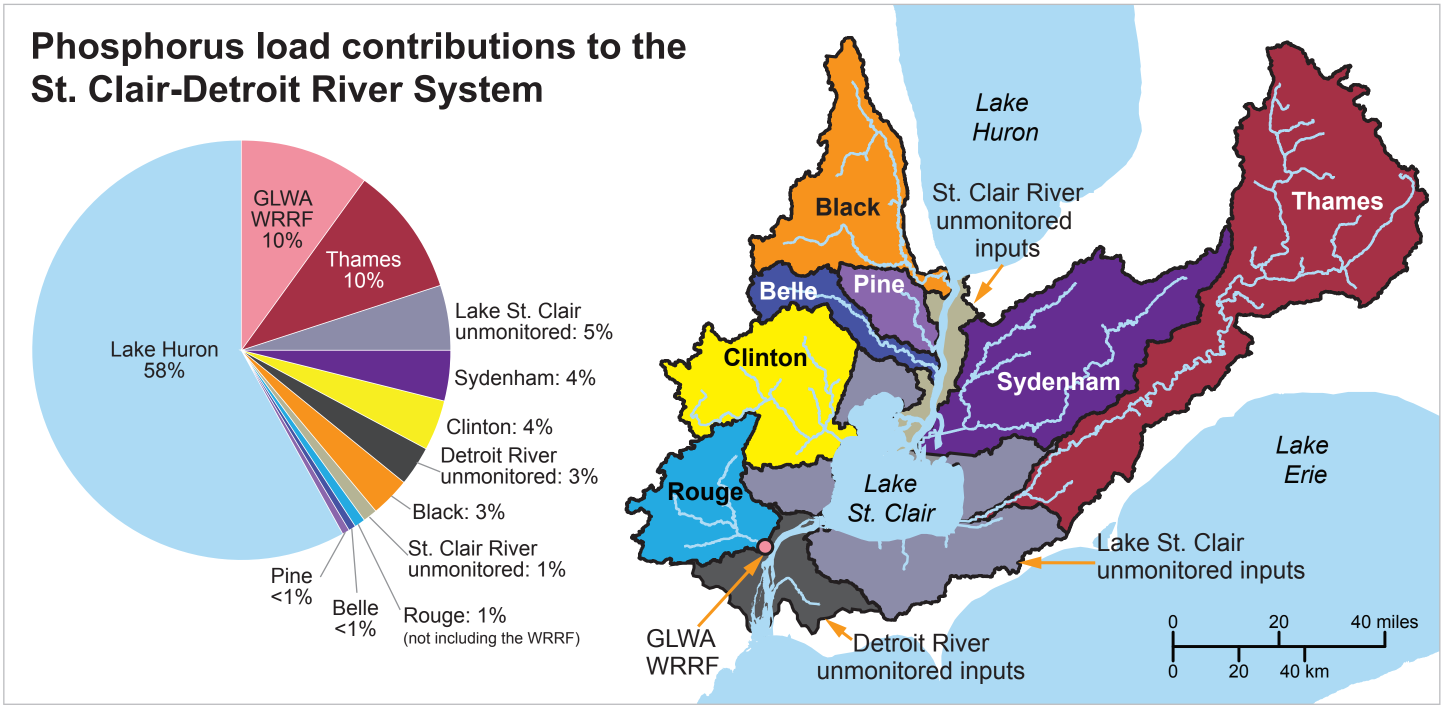

Figure B. ***Where is phosphorus coming from?*** The pie chart shows the relative amounts of phosphorus that come from different parts of watershed. Colors in the pie chart correspond to the map at right. The Thames and Sydenham river watersheds are primarily agricultural, while the Clinton and Rouge are mostly urban. The Great Lakes Water Authority's Water Resource Recovery Facility (GLWA WRRF) in Detroit is one of the largest wastewater treatment facilities in North America and serves 77 communities. Some of the phosphorous inputs that flow through Lake St. Clair are retained and removed from the water, which is not accounted for in this figure. Accounting for retention in Lake St. Clair slightly increases the relative contribution of downstream sources, such as the WRRF in Detroit, that do not pass through Lake St. Clair before entering Lake Erie.

records of flow and nutrient input to and output from the lake and developed a detailed biogeochemical lake model.

Through both analytical approaches, we found that Lake St. Clair is a net sink for phosphorus; a portion of the phosphorus that enters the lake remains there. Our long-term data analysis indicated that the lake retains, on average, 20% of its total phosphorus input, but retention of dissolved reactive phosphorus is likely much lower than that. While the introduction of zebra and quagga mussels and the production of aquatic plants could account for much of the retention, sediment accumulation is possible in the 30% of the lake bottom that is deeper than 15 feet. Wind-induced resuspension over the remaining 70% could explain the year-to-year variability in retention rates in the lake.

We compared retention rates of flows and sediments from the lake's major tributaries and found lower retention rates of inputs from the Thames River. This suggests that changes in the Thames River load are likely to result in larger changes in the load leaving the lake, compared to changes in the Sydenham or Clinton river loads. However, changes are likely to be small compared to the overall load to the lake which is dominated by the St. Clair River.

4. URBAN SOURCES ASSESSMENT

Twenty percent of land area in the St. Clair-Detroit River System watershed is urban. The largest urban areas are around Detroit, Michigan and London and Windsor, Ontario. These three urban areas together contribute 24% of the phosphorus load carried by the Detroit River to Lake Erie. We found that point sources, which include wastewater treatment plants and, to a lesser extent, industrial facilities, are responsible for 80% of the phosphorus from urban areas. The Water Resources Recovery Facility in Detroit treats sewerage from 77 communities and is the largest urban source of phosphorus, representing about 63% of the load from the Michigan urban study area and about 13% of the Detroit River's load to Lake Erie. Our analysis found that the plant has reduced its load by 44.5% since 2009 by improving treatment. Stormwater runoff accounts for 10% of urban phosphorus contributions. The remainder of the urban load comes from treated (7%) and untreated (2%) combined sewer overflows (CSOs). While contributions to the Detroit River load from runoff and CSOs are relatively minor, even as a percentage of the urban load, efforts to reduce these events can have environmental benefits beyond phosphorus reduction.

5. OPTIONS FOR REDUCING LOADS FROM AGRICULTURAL SOURCES

We used the Soil and Water Assessment Tool (SWAT) to model the entire St. Clair-Detroit River System watershed and to explore options for reducing phosphorus loads. Although the model is of the entire study area, including all point sources, it is particularly well suited to evaluate how changes in agricultural land management practices could impact runoff, nutrient losses and downstream water quality. Several land management practices were found to be effective in reducing total and dissolved forms of phosphorus from agricultural watersheds; however, no practice implemented alone could achieve a 40% reduction.

The biggest reductions in phosphorus loads were achieved by combining three of the following practices: planting cover crops, adding filter/buffer strips, creating or restoring wetlands, and placing fertilizer and manure into the soil. These combinations resulted in greater than 50% reductions in phosphorus from the agricultural watersheds and suggest that a flexible approach, where practices can be combined to match the needs and preferences of farmers, will be most successful. Our analysis suggests that focusing these practices on 55% of the land with the highest per acre losses of phosphorus could achieve reductions on the order of the *Great Lakes Water Quality Agreement* targets. For the Thames River, we found that the practices that meet the annual target loads also meet the spring targets. Compared to similar areas in Michigan, the Ontario watersheds had higher modeled phosphorus loss yields per acre of agricultural land, especially for dissolved reactive phosphorus, most likely because they receive more rainfall.

6. OPTIONS FOR REDUCING LOADS FROM URBAN AND SUBURBAN SOURCES

To explore options for reducing urban loads, we calibrated a Storm Water Management Model (SWMM) for the large combined sewer area in and around Detroit. This fine-resolution urban model focused on metro Detroit, but the strategies explored are relevant to London, Windsor, and other cities that experience wet weather discharges from a combined sewer system.

Because the load from the regional Water Resources Recovery Facility (WRRF) in Detroit is the largest urban phosphorus source, improvements in treatment efficiency at this facility could help reduce loads to Lake Erie. However, significant additional treatment improvements beyond what has already been done over the past decade could become expensive. SWMM results suggest that reducing combined sewer overflows could be difficult by relying solely on efforts to reduce the cover of impervious surfaces such as pavement. While CSOs higher in the sewer collection system can be addressed to an extent through approaches such as green infrastructure, downstream overflows are caused by water coming from many upstream subcatchments and thus are difficult to address locally. SWAT modeling results for the highly urban Clinton and Rouge watersheds indicate that creating vegetated pervious surfaces is more effective for reducing phosphorus loads than creating pervious surfaces without vegetation such as permeable pavement.

7. OPTIONS FOR MEETING PHOSPHORUS LOADING TARGETS

Through this report and referenced journal articles, we have provided a more complete understanding of the relative contributions of different sources of phosphorus within the St. Clair-Detroit River System watershed, including Lake Huron, point sources, combined sewer overflow events, and runoff from both agricultural and urban lands. We have documented some significant reductions in phosphorus inputs over time due to ecological and climatic changes in Lake Huron and improvements at the regional Water Resource Recovery Facility in Detroit, but additional work is needed to reach phosphorus targets (Figure C).

As the US and Canada adaptively manage their Domestic Action Plans for reducing loads to Lake Erie, findings from this project may help them reevaluate the basis for load reductions from the St. Clair-Detroit River System watershed.

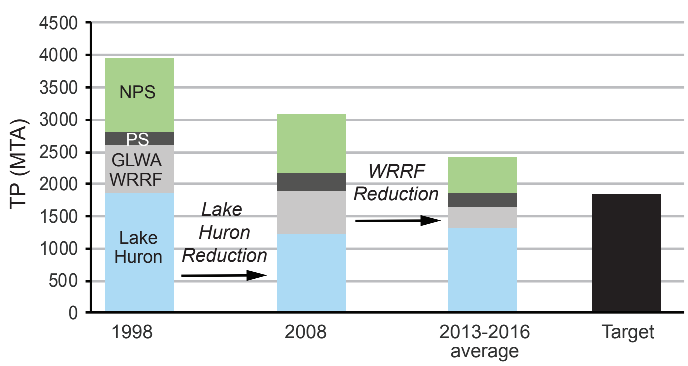

Figure C. ***How have inputs changed over time?*** This bar chart shows the annual amount of phosphorus input to Lake Erie from the Detroit River during three time periods. The colors represent four sources of phosphorus: (1) flow from Lake Huron; (2) discharge from the Great Lakes Water Authority Water Resource Recovery Facility (GLWA WRRF) in Detroit; (3) discharge from other point sources (PS) in the watershed; and (4) runoff from nonpoint sources (NPS) in the watershed. The target represents a 40% reduction from the 2008 load.

For example, our new understanding of the contribution from Lake Huron suggests that reaching Lake Erie loading targets may require larger reductions from the watershed than previously thought, and attention to Lake Huron sources. We also identified a need to enhance monitoring around the outlet and southeastern shore of Lake Huron to better understand the phosphorus load from the lake. This report identifies several pathways for reaching load reduction targets, including placing a combination of agricultural land management practices on lands with higher losses of phosphorus, and strategies to capture and manage wet weather flows in combined sewer systems, including strategic use of green infrastructure for CSO retention basins with smaller collection areas.

Most climate models predict that this region will experience warmer temperatures and greater precipitation in the future, including more frequent and intense storms in the spring and summer. Our watershed modeling indicates that these precipitation changes will lead to more runoff and greater phosphorus loading from agricultural areas as well as from the already stressed combined sewer systems. The projected warmer temperatures are expected to mitigate these impacts somewhat through a longer growing season, more evapotranspiration by plants, and smaller snowmelt events. Climate change is likely to make nutrient reduction efforts more challenging, but knowledge of future climate impacts can inform action now, for example, by elevating the need for water management strategies to accompany nutrient management. In summary, this modeling-based project integrated and analyzed extensive datasets to develop results that can be used to guide policies and practices as the countries work within the *Great Lakes Water Quality Agreement* adaptive management framework.

1 INTRODUCTION

ALGAL BLOOMS AND DEAD ZONES RETURN TO LAKE ERIE

Among the Great Lakes, Lake Erie is the warmest, shallowest, and most productive, contributing to its sensitivity to phosphorus loading. In the 1960s and 70s, increasing phosphorus inputs led to severe algal blooms in the lake's western basin and periods of low oxygen (hypoxia) in the bottom waters of its central basin. Phosphorus abatement programs, initiated as part of the 1972 *Great Lakes Water Quality Agreement* (GLWQA), prompted wastewater treatment facilities to add secondary treatment, phosphorus was removed from most soaps and detergents, and soil conservation programs were enhanced. These changes reduced the amount of phosphorus released into the lake and led to clear improvements in water quality and fisheries.

However, in the mid-1990s, water quality degraded as western-basin harmful algal blooms and central-basin hypoxia returned with conditions similar to the 1960s and '70s, impacting fishing, swimming, tourism, and drinking water systems. Results from monitoring programs, lake models, and experimental studies showed that the increasing spring load of dissolved reactive phosphorus (DRP)[1] from the Maumee River watershed was the primary driver of the western basin algal blooms, and that the annual load of total phosphorus (TP)[2] to the western and central basins was the primary driver of hypoxia.

In 2012, the United States and Canada signed a revised GLWQA that required new Lake Erie phosphorus loading targets and associated action plans. In response to this commitment, they adopted the following phosphorus reduction targets, compared to a 2008 baseline. Items related to this study are in bold:

- Related to central-basin hypoxia, a **40% reduction in the annual western and central basin TP load.**
- Related to healthy nearshore ecosystems, a **40% reduction of spring (March-July) TP and DRP loads from the Thames River,** Leamington tributaries, Maumee River, River Raisin, Portage River, Toussaint Creek, Sandusky River, and Huron River (Ohio).
- Related to western-basin cyanobacteria blooms, a 40% reduction in Maumee River spring TP and DRP loads.

In 2016 the Erb Family Foundation provided support to this project to characterize phosphorus sources and evaluate management options for the St. Clair-Detroit River System watershed. It addresses the Detroit River contribution to the first target (above) and the Thames River component of the second target.

As the US and Canada develop and implement Domestic Action Plans to reduce phosphorus loads, substantial attention will logically be placed on loads from the Detroit and Maumee rivers because they have been reported to contribute 41% and 48%, respectively, of the TP load to the western basin, and 25% and 29% of the TP load to the whole lake (Maccoux et al. 2016; Scavia et al. 2016). There have been

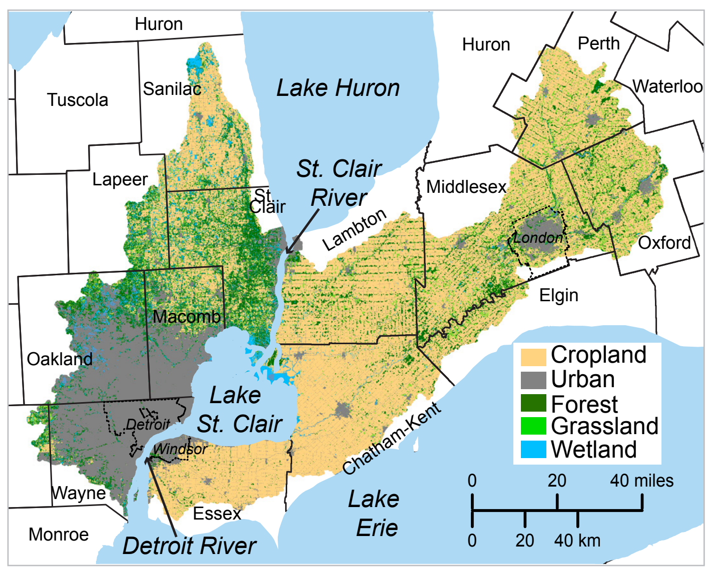

Figure 1. Land use in the project study area- the St. Clair-Detroit River System watershed. Counties and major cities are labeled. The watershed is composed of about 49% cropland, 21% urban land, 13% forest, 7% grassland, 7% surface water (including Lake St. Clair), and 3% wetlands.

[1] **Dissolved reactive phosphorus (DRP)** and soluble reactive phosphorus (SRP) are terms used interchangeably for the form of phosphorus most readily available for algae growth. The documents forming the *Great Lakes Water Quality Agreement* and the Domestic Action Plans refer to it as SRP. This report, the papers upon which it is based, and a growing recent literature refer to it as DRP.

[2] **Total phosphorus (TP)** refers to all forms of phosphorus found in a sample of water or soil, including sediment bound P as well as more readily soluble forms. Dissolved reactive phosphorus (DRP) is one component of TP.

several assessments of the relative contributions and potential controls of phosphorus loads from the Maumee watershed (e.g., Scavia et al. 2017, Muenich et al. 2017, Kalcic et al. 2019). This study is similar in that it assesses management strategies for the US and Canadian watersheds that deliver phosphorus to the St. Clair-Detroit River system and then to Lake Erie (Figure 1).

LINGERING QUESTIONS ABOUT THE DETROIT RIVER'S CONTRIBUTION TO LAKE ERIE

The sources contributing to the Detroit River's phosphorus loads have been somewhat uncertain due to limited data and a historical lack of attention to its watershed. This uncertainty complicates efforts to develop a regional strategy for reducing phosphorus to Lake Erie. Understanding where these nutrients originate is critical for developing load reduction plans and deciding what level of emphasis should be placed on different tributaries or different nutrient sources (e.g., point sources, agricultural runoff).

This watershed is also complicated by the presence of Lake St. Clair, which processes the phosphorus load from its watershed and the St. Clair River. Whether the lake is an ultimate source of, or sink for, phosphorus, and whether loads from different tributaries (e.g., Clinton, Sydenham, Thames, St. Clair rivers) have equally significant impacts downstream, have been unclear.

In addition to the lack of information about the source and amounts of Detroit River phosphorus loads, it has been difficult to monitor what the river, in turn, delivers to Lake Erie because the connecting channels (i.e., the St. Clair and Detroit rivers) are large and not well mixed. This requires extensive sampling across the rivers and over time to develop accurate measures. Also, Lake Erie seiches occasionally cause flows to back up into the river, influencing estimates of river discharge.

PROJECT OBJECTIVES AND APPROACH

Objectives - Our objectives were to engage stakeholders from US and Canadian public and private sectors to:

- Quantify the sources of phosphorus entering Lake Erie from the Detroit River;
- Understand how various phosphorus sources contribute to the Detroit River's load to the lake; and
- Evaluate options for reducing those loads.

Advisory group - At the project inception, we established an advisory group to help us better understand the policy contexts, and to provide feedback on our planned research approach and resulting products. The advisory group included US and Canadian representatives from federal, state, and provincial governments; non-profits; universities; industry representatives and local organizations actively involved in watershed management, policy development, or research (See Appendix A for the full list of group members and report supplemental information for an outline of meetings and summary of specific contributions of the advisory group).

Through annual in-person meetings, periodic conference calls, and individual consultations, the 30-person advisory group helped ensure that our research would be scientifically credible, and the results would be relevant and usable for the Great Lakes policy and management communities.

INTERPRETING MODELING RESULTS

This project relies heavily on different types of mathematical models to simulate flow and nutrient dynamics. We calibrated and validated widely used modeling frameworks (e.g., SWAT, SWMM, ELCOM-CAEDYM) using extensive physical, chemical, biological, and land-use data from both the US and Canada. We used these calibrated models to estimate nutrient loads and evaluate "what if" scenarios. We use the term "scenario" to refer to a specific test we conducted with a model, altering one or several parameters from their baseline conditions to simulate the potential impact of making a particular change to land management or land use. These scenarios were not necessarily intended to represent realistic possibilities, but rather to help us understand how the watershed works and compare strategies for nutrient reduction.

All models have limitations and modeling results should be interpreted and applied carefully. As is typical for this type of research, analyses at long time and large spatial scales (e.g. our system-wide, annual mass balance model) are more certain than those at short time and small spatial scales. As such, we believe our modeling results at those smaller scales are most useful if viewed as a guide to understanding how watersheds like this one are likely to respond to alterations, not as precise predictions or proscriptions.

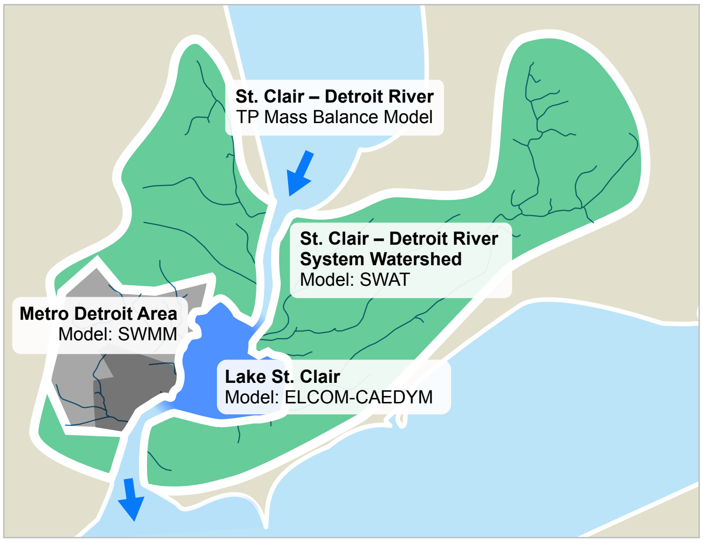

Figure 2. The four models used in this study.

Feedback from the group helped identify key areas of interest, potential concerns, and new data sets and related projects that influenced the team's approach, baseline assumptions, and specific analyses for modeling runs (Goodspeed et al. 2018). Although all members of the advisory group had opportunities to comment on project results and research summaries, the content of the report is solely the responsibility of the project team.

Technical analysis - Our approach was based on the construction and use of four models (Figure 2) that simulate the dynamics of this complex watershed:

- A **mass balance model** that accounts for all flows and phosphorus inputs to and outputs from the system on an annual basis between 1998 and 2016 (Scavia et al. 2019), and an additional, detailed accounting of phosphorus sources from the three largest urban areas (Hu et al. in review).
- A **watershed model** of the entire project watershed that simulates the flow and dynamics of water, nutrients, and sediment on daily-to-annual time scales at relatively small spatial scales for 2001-2015. This model is based on the widely used Soil and Water Assessment Tool (SWAT) (Dagnew et al. 2019a).
- A **3-dimensional ecosystem model of Lake St. Clair** (ELCOM-CAEDYM) that simulates nutrient and algae dynamics at daily time scales for 2009 and 2010 to explore nutrient transport and retention in the lake, as well as relative influence of its tributaries (Bocaniov and Scavia 2018).
- An **urban model** to characterize the dynamics of loads from the metro Detroit area. This model is based on the widely used Storm Water Management Model (SWMM) (Hu et al. 2018).

Technical documentation - The bulk of the information in this report is based on a series of papers published in peer-reviewed literature. Because the journal review processes for some of these papers were not completed at the time of this report's release, we have provided drafts for those papers on our project website (myumi.ch/detroit-river), and these will be updated as the papers are published.

REPORT ORGANIZATION

The remainder of the report is organized into chapters as follows:

2. ***Overview of Phosphorus Sources*** provides a big picture assessment of the watershed's primary nutrient sources and how they have changed between 1998 and 2016.
3. ***Nutrient Processing in Lake St. Clair*** provides an analysis of the lake's phosphorus retention capacity and compares the potential impacts of reducing loads from its major tributaries.
4. ***Urban Sources Assessment*** provides an analysis of phosphorus from point sources, combined sewer overflows, and runoff in urban areas in Michigan and around Windsor and London.
5. ***Options for Reducing Loads from Agricultural Sources*** provides results from the watershed model on the relative effectiveness of various management practices in reducing phosphorus loads, primarily from nonpoint sources.
6. ***Options for Reducing Loads from Urban and Suburban Sources*** provides an analysis of the relative impacts of changes in land cover and system operations on point sources, combined sewer overflows, and runoff.
7. ***Summary of Options*** brings together the information on agricultural, suburban, and urban analyses to explore overall options for reducing loads to meet the Great Lakes Water Quality Agreement targets.

2 OVERVIEW OF PHOSPHORUS SOURCES

The Detroit River provides approximately 80% of the flow that enters Lake Erie. Nutrient concentrations in the Detroit River are relatively low compared to the Maumee River, but discharge is much greater. The Detroit River, therefore, delivers a large annual TP load that contributes significantly to central-basin algae production and sedimentation and, ultimately, to the extent of hypoxia. But because phosphorus concentrations are low, the flow tends to dilute nutrients in the western basin. As a result, it is not a significant driver of the western-basin algal blooms, which are driven primarily by the Maumee River's spring load. The mixing zone between the Detroit River and western basin water is visible in satellite images where algae and sediment concentrations closer to the mouth of the Detroit River are lower (Figure 3), and the water tends to move quickly into the central basin.

RESULTS AT A GLANCE

- The Detroit River annual TP load is the total mass of phosphorus transported by the river to Lake Erie over the course of a year. On average, 54% of Detroit River TP load comes from Lake Huron.
- The highest watershed TP loads are from the regional Water Resource Recovery Facility in Detroit and the Thames watershed (where the load is mainly from nonpoint sources), followed by the Sydenham, Clinton, and Black watersheds.
- From the US: 63% of watershed TP loads and 74% of watershed DRP loads are from point sources.
- From Canada: 83% of watershed TP load and 82% of watershed DRP loads are from nonpoint sources.
- Detroit River loads have declined over time, largely because of improvements in water treatment at the Water Resource Recovery Facility in Detroit and earlier changes in Lake Huron ecology.

APPROACH FOR MASS BALANCE ANALYSIS

We compiled and analyzed data from US and Canadian water quality monitoring programs between 1998 and 2016. Most of the information in this chapter comes from the publication, "*St. Clair-Detroit River system: Phosphorus mass balance and implications for Lake Erie load reduction, monitoring, and climate change*" by Scavia et al. (2019).

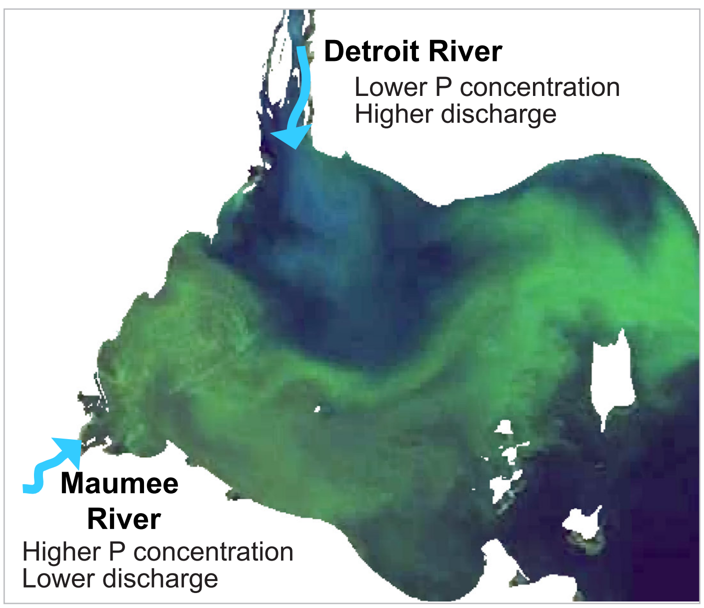

Figure 3. Image of the Western Lake Erie Basin in September 2015. The algal bloom originating from the mouth of the Maumee River is diluted and pushed away by the high volume of water with low phosphorus concentration entering from the Detroit River.

The journal article describes in detail how we calculated and analyzed point and nonpoint source contributions from the watershed. In short, we used standard methods to calculate tributary phosphorus loads based on concentration and flow data for gauged tributaries, ungauged tributaries, and the connecting channels (St. Clair and Detroit rivers) (Figure 4). We also compiled discharge data from US and Canadian government agencies for point sources, such as wastewater treatment plants and factories, and for combined sewer overflows.

Because there can be substantial year-to-year variability in flow and loads, we used the four-year average of the ***2013 through 2016*** water-years to represent ***current sources*** throughout this report. This current time period is compared to average loads going back to 1998 to assess trends over time. All years referred to are water years (i.e., October through September. For example "2013" means October 2012 through September 2013).

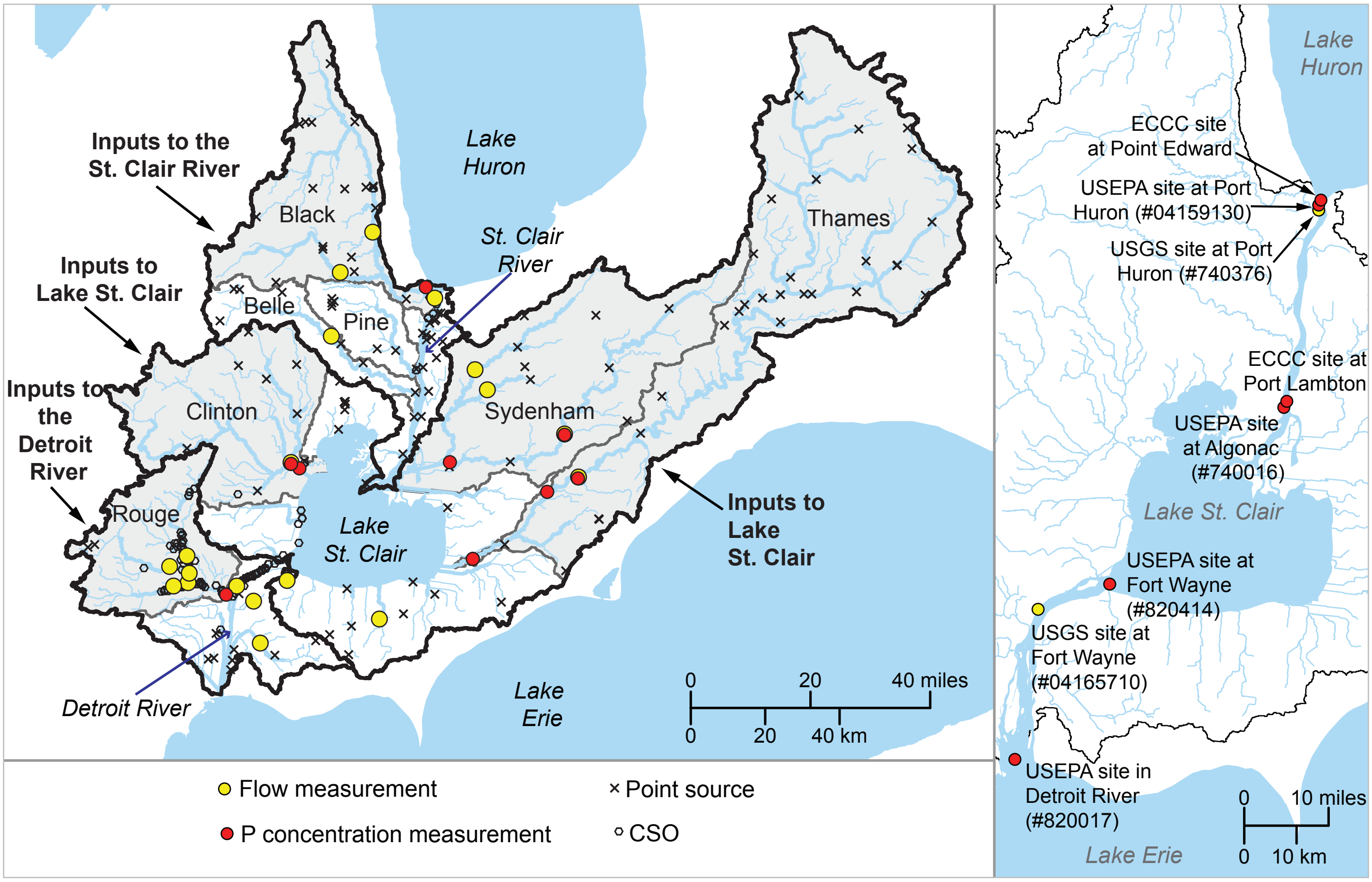

Figure 4. Map of the St. Clair-Detroit River System watershed, identifying major tributaries and their watershed boundaries (gray lines), and areas contributing to different water bodies (bold black lines). Shaded areas represent watersheds with monitoring programs; non-shaded areas have more limited monitoring and loads were calculated using a different method. Flow and phosphorus measurement locations represent data used for the mass balance analysis and may differ from locations used for analyses in other chapters of this report.

KEY CHARACTERISTICS OF MAJOR WATERSHEDS IN THE STUDY AREA

The **Black River (MI)** watershed is 67% agricultural land, 17% forested, and 8% urban. Agriculture includes primarily corn, soy, and wheat crops, with some sugar beet production and a few livestock operations in the upper reaches. The soils are moderately well drained with tile drainage on an estimated 59% of the farms. The Black River's long-term monitoring data were used for model calibration, and monitoring shows fairly low TP loads and particularly low DRP loads. Two adjacent smaller river basins - the Pine and Belle - are expected to respond similarly to the Black to land management scenarios. In comparison with Ontario agricultural lands in our study area, Black River farm lands show relatively lower losses of DRP per acre, which seems to be primarily driven by comparatively lower rainfall and less runoff in this watershed. Other factors could include more forested areas mixed in with farm lands, lower fertilizer application rates, and wider spacing between tile drains (see Figures 25-27 in Chapter 5). Agricultural management practices tested in this study had relatively little impact on DRP loads in this watershed, in part because DRP losses appear to be low already.

The **Clinton River (MI)** watershed is 52% urban, 20% forested, and 18% agricultural land. The Clinton River and its tributaries flow through 60 rural, suburban, and urban communities with a total population of more than 1.4 million, including some urbanized areas considered part of metro Detroit. This watershed includes a number of small point sources, such as wastewater treatment facilities, that are included in all modeling calculations. These point sources are not affected by land management scenarios and thus help explain the relatively lower reductions achieved by agricultural land management practices in this watershed (Chapter 5).

KEY CHARACTERISTICS OF MAJOR WATERSHEDS IN THE STUDY AREA

The **Rouge River (MI)** watershed includes the City of Detroit and many surrounding suburbs. 84% of this watershed is urban, 8% is forested, and 5% is agricultural. Approximately 19% of the watershed has a combined sewer system, and some runoff in this area flows to the regional wastewater treatment plant in Detroit, the Great Lakes Water Authority Water Resource Recovery Facility (WRRF). The outfalls for the facility are located just outside this watershed, so loads from the facility are reported separately from the Rouge watershed loads, and WRRF loads are not considered when reporting percent reductions for land management scenarios in Chapter 5. Chapter 6 examines some of the options for reducing loads from the combined sewer collection area and treatment plant.

The **Sydenham River (ON)** watershed is 82% agricultural land, 11% forest, and 5% urban with no major urban areas. The major crops are soybeans and corn. Much of this watershed is relatively flat (<2% slopes) with naturally imperfectly drained to poorly drained soils. To improve drainage, 77% of the farm fields have subsurface tile drainage systems installed. The receiving drainage channels in some areas, particularly around Lake St. Clair, are equipped with pumping (lift) stations to further manage drainage water levels in these municipal ditches and the adjacent fields.

The **Thames River (ON)** watershed is 77% agricultural, 10% urban, and 12% forest, including extensive areas with corn, soybeans and wheat, as well as a number of livestock operations in the upper reaches of the watershed. The City of London is located near the center of this watershed with a population of 383,000. Much of the upper Thames (i.e. north and east of London) has gently rolling topography with more coarse soils, while the lower Thames area has relatively flat topography and soils with increasingly more clay. Tile drains have been placed in 59% of farm fields. In the lower reaches of the watershed, tile drainage systems are more common and pumps help manage drainage waters. Rainfall is significantly higher in its upper reaches in comparison with other parts of the St. Clair-Detroit River System watershed. The Thames river basin is the largest watershed in this study area. Model calibration was based on two monitoring stations, one in the upper portion and one in the lower portion of the Thames river basin.

There are a number of **smaller drainage** basins that flow directly to the St. Clair River, Lake St. Clair, and the Detroit River, including Essex County in Ontario and towns such as St. Clair Shores in Michigan. These smaller watersheds, particularly in Ontario, include extensive and highly productive croplands. The drainage basins in this area are generally quite flat with naturally imperfectly drained to poorly drained clay loam or clay soils. Tile drainage systems have been installed on approximately 70% of the area's farms. The City of Windsor with a population of 217,000 is located within this area in Essex County alongside the Detroit River. Different methods were used to estimate nonpoint source loads from these smaller drainages and they are labeled as "unmonitored" in Chapter 2. Our watershed model includes these drainage basins, but land management scenario results were not reported for this area (Chapter 5).

ORIGINS OF DETROIT RIVER PHOSPHORUS

Revised Detroit River loads - Our estimate of the 2008 Detroit River total phosphorus (TP) load is 3,096 MTA[3]; a 40% reduction would result in a new target load of 1,858 MTA. However, because the 2013-2016 average Detroit River loads had already declined to 2,425 MTA, there is a 567 MTA reduction remaining to reach the target.

Our estimates of the Detroit River TP load are higher than those estimated by Maccoux et al. (2016) and lower for two of the three years estimated by Burniston et al. (2018) (Figure 5). The differences can likely be explained by differences in the ways the loads were calculated in the three studies. Our estimates are based on summing the load from Lake St. Clair and all other sources to the Detroit River downstream of Lake St. Clair using USGS's WRTDS[4] method for tributaries on the

[3] Metric Tonnes per Annum - or MTA - is a measure of the total amount of phosphorus delivered by a tributary or discharged by a point source into a receiving body over the course of a year. A metric tonne is 1000 kg or 2204.62 pounds.

[4] **WRTDS** is the Weighted Regressions on Time, Discharge, and Season method for calculating tributary loads from continuous river flow and discrete water quality concentrations. It has been shown to have several advantages over the Load Estimator (LOADEST) because the flow-concentration relationships can vary over time. Both rely on statistically significant relationships between flow and concentration, and because those relationships are very weak in the connecting channels, neither approach is appropriate there.

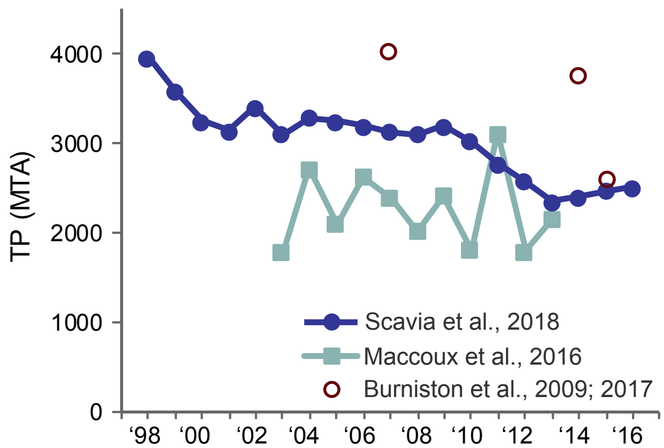

Figure 5. Our calculated TP loads to Lake Erie (dark blue line) compared to other published loads calculated with different methods.

downstream watersheds. Because WRTDS is not appropriate for connecting channels, we multiplied concentrations and flows at the outlet of Lake St. Clair to calculate its load. The Maccoux et al. (2016) estimate is based on summing all of the loads, estimated with the stratified Beale ratio method, to the St. Clair and Detroit rivers. Their estimates are low because they used what has subsequently been shown to be low Lake Huron load estimates (Burniston et al. 2018, Scavia et al. 2019). The Burniston et al. estimates are based on Detroit River TP concentrations measured upstream of the influence of Lake Erie. They used the USGS LOADEST method which,

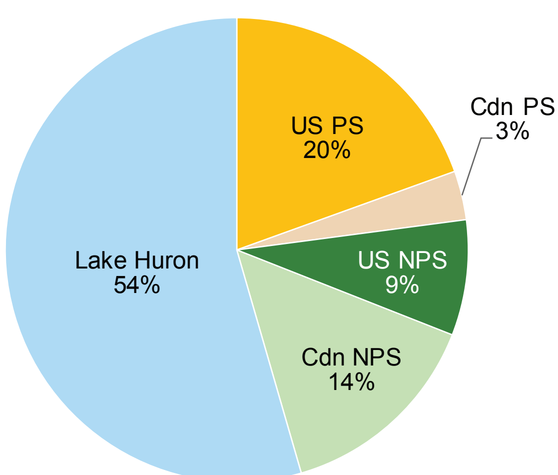

Figure 6. Proportions of the Detroit River's TP load to Lake Erie from Lake Huron and US and Canadian point sources (PS), which includes combined sewer overflows, and nonpoint sources (NPS). This calculation takes into account retention in Lake St. Clair.

like WRTDS, may not be appropriate for connecting channels. The Maccoux et al. estimates were used by the US and Canada as the 2008 baseline when they determined load reduction targets for the binational agreement; the implications of our new estimates are discussed in Chapter 7.

Phosphorus from Lake Huron dominates the Detroit River load – Our analysis shows that Lake Huron contributes more than half of the Detroit River TP load[5] to Lake Erie (Figure 6), considerably more than in previous studies (Maccoux et al. 2016; Burniston et al. 2018). This updated estimate of the Lake Huron contribution does not impact our estimates of the Detroit River load because our estimate relies on measurements at the outlet of Lake St. Clair, which effectively captures the full Lake Huron contribution. However, as we will discuss in Chapter 7, it does impact the potential allocation of load reduction targets for the system.

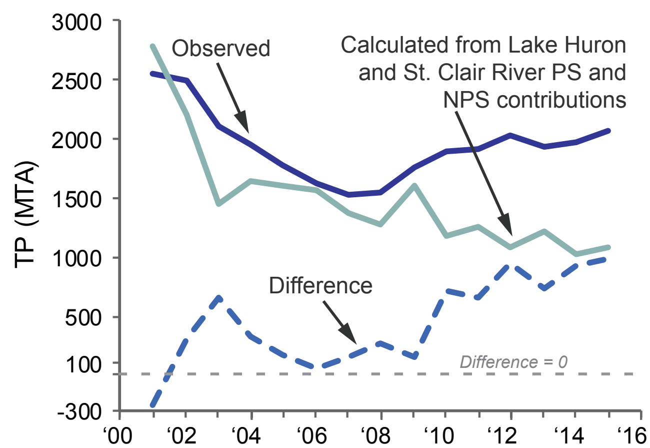

Figure 7. TP inputs to Lake St. Clair measured at Algonac and Port Lambton (dark blue line) and calculated from Lake Huron and the St. Clair River point and nonpoint source contributions (sage line). See Figure 4 for sample locations. The difference (dashed line) represents the portion of the load that is entering Lake St. Clair but not accounted for in monitoring data.

Burniston et al. (2018) noted that the load entering Lake St. Clair was considerably higher than that leaving Lake Huron. Our study also showed this (Figure 7), and we demonstrated that the difference was not because St. Clair River watersheds were contributing the additional phosphorus. This unmeasured load is sizeable and increasing over time, approaching the value estimated from summing the measured loads from Lake Huron and the St. Clair River

[5] The **Detroit River TP load** refers to the total mass of phosphorus that is transported by the Detroit River to Lake Erie over the course of the year, including contributions from Lake Huron and the St. Clair–Detroit River System watershed. When reporting contributions to the Detroit River P load, we have accounted for retention in Lake St. Clair (discussed in Chapter 3).

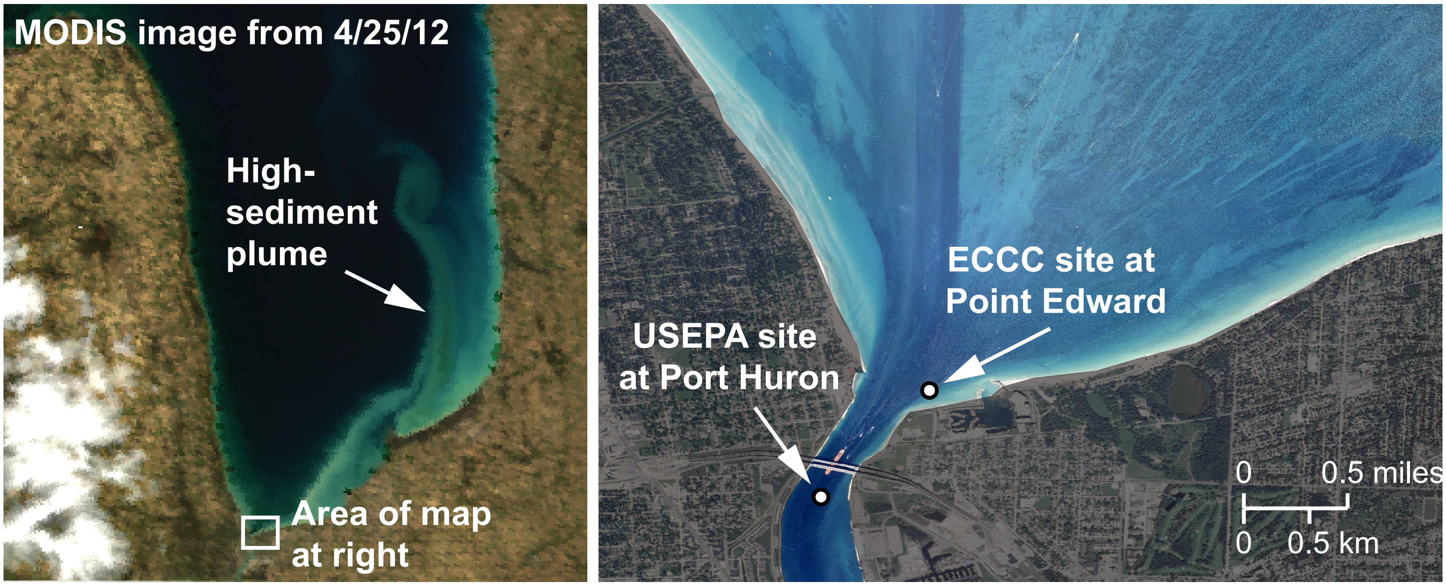

Figure 8. *Left:* True-color satellite image showing a high-sediment resuspension event. *Right:* Monitoring stations around the head of the St. Clair River. Only data from the Environment and Climate Change Canada (ECCC) site at Point Edward showed these events, but the sampling there is not frequent enough to capture them all.

watershed (gray and dashed lines in Figure 7). We believe this increase is due, in part, to climate-driven declining ice cover and an increasing frequency of large storms, which result is an increase in resuspension of sediment in Lake Huron and its subsequent transport to the St. Clair River (Scavia et al. 2019).

To better understand the phosphorus load from Lake Huron, we further analyzed data from the two monitoring stations (Figure 8) around the head of the St. Clair River along with remote sensing images of Lake Huron. Analysis of satellite imagery revealed large sediment plumes frequently occurred along the southeastern shore of Lake Huron (Figure 8), likely driven by the high winds and waves and, in winter, reduced ice cover. These resuspension events can persist for days, with currents moving the sediment along the Canadian shore to the St. Clair River, evading detection at the Point Edward

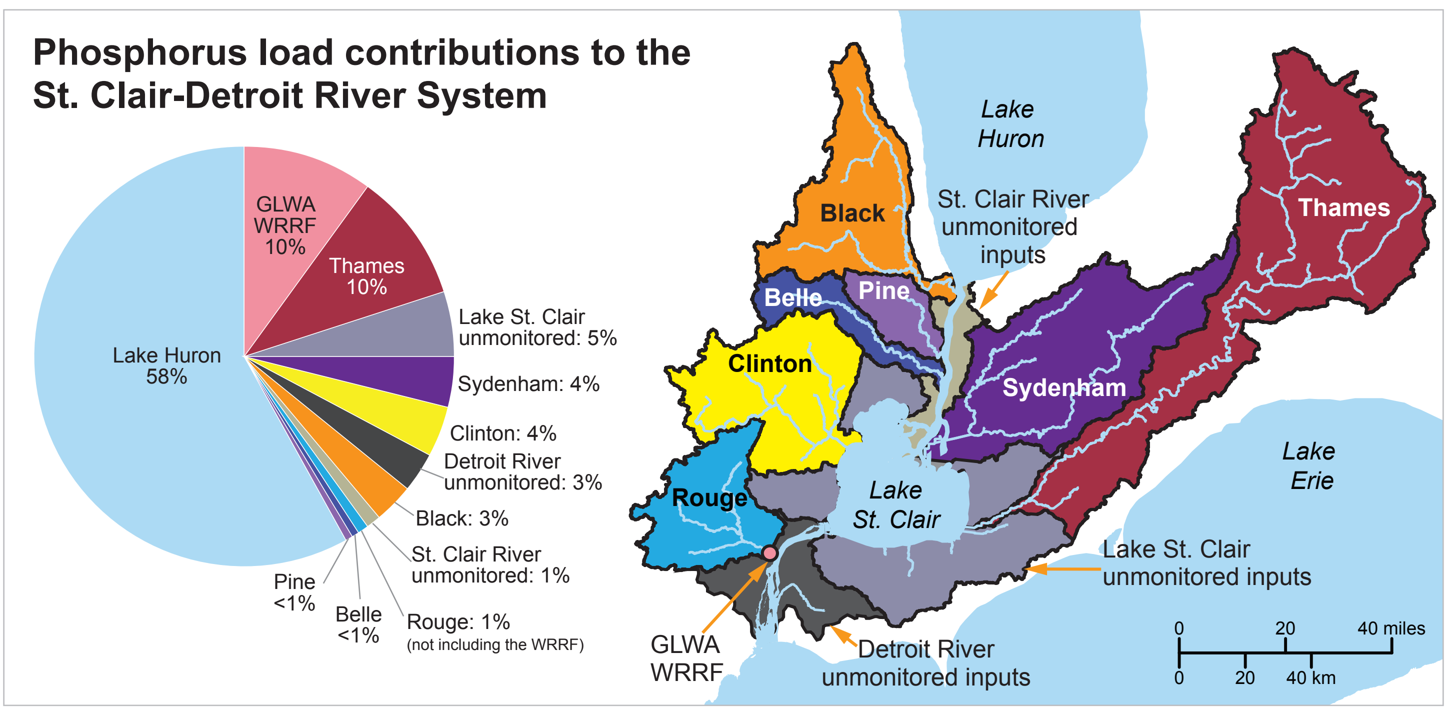

Figure 9. Proportions of the TP load from all of the system's sources. Colors in the pie chart correspond to the map at right. Note that the GLWA WRRF is in the Rouge watershed, but is shown separately in the pie chart. These estimates do not account for retention in Lake St. Clair.

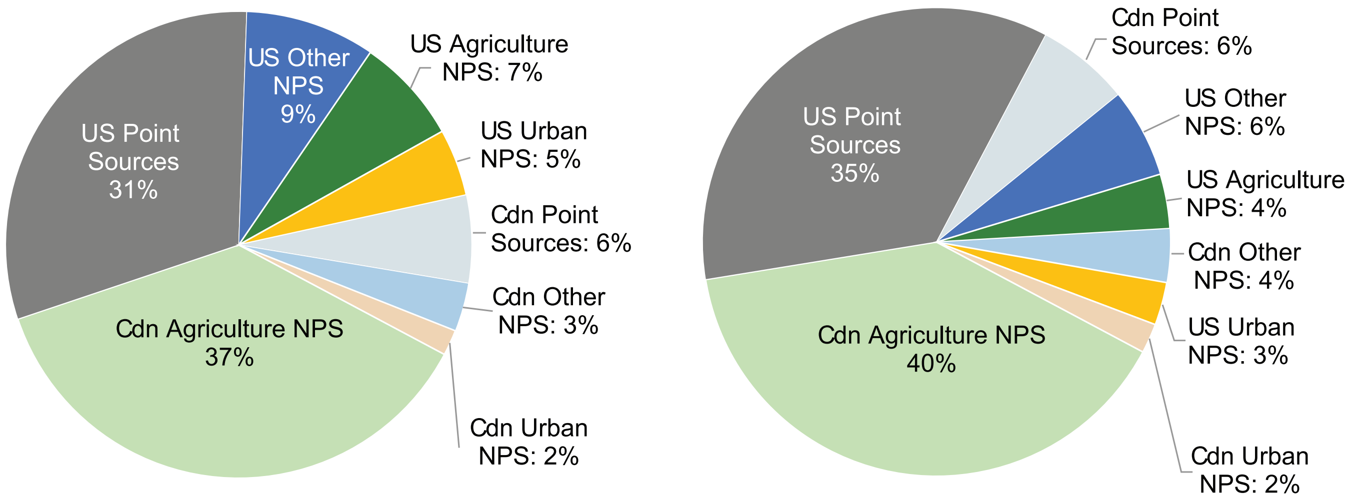

Figure 10. Proportions of the watershed TP *(left)* and DRP *(right)* loads from US and Canadian point sources, as well as non-point sources (NPS) coming from agricultural land (i.e., cropland and pastureland), urban land, and other land (i.e., forests and wetlands). Nonpoint source allocations are derived from SWAT. The load from Lake Huron is not included here.

monitoring station. We showed that sampling at that station could detect these events, but the sampling is not frequent enough to catch many of them.

Watershed sources of phosphorus - After Lake Huron, the largest sources of phosphorus are the Great Lakes Water Authority Water Resource Recovery Facility (GLWA WRRF), followed by the Thames River watershed, unmonitored loads to Lake St. Clair, and the Sydenham and Clinton river watersheds (Figure 9). The remaining 10% of the system's load comes from unmonitored areas that drain to the Detroit and St. Clair rivers, and the Black, Rouge, Belle, and Pine river watersheds. We use the term "watershed load" to refer to the load from sources excluding Lake Huron.

Nonpoint sources - Nonpoint sources provide 57% of the watershed TP load and 50% of the dissolved reactive phosphorus (DRP) load. With the Soil and Water Assessment Tool (SWAT, Chapter 5), we determined how much of the load comes from nonpoint sources on agricultural land (including cropland and pasture), urban land, and other land areas (primarily forests and wetlands) (Figure 10). Agricultural nonpoint sources contribute 44% of the TP load and 44% of the DRP load, reflecting both the intensity and extent of agriculture in this watershed. The watershed contains some of Canada's most productive farmland, including extensive row crops in the lower parts of the watershed and livestock operations in the upper part. Urban and suburban nonpoint sources (e.g., roadway runoff and runoff from other impervious surfaces, animal waste, turf fertilizer, leaf litter) account for 7% of the watershed load (Figure 10).

Point sources - Point sources make up about 43% of the watershed TP load, with 502 MTA coming from US point sources and 100 MTA from Canadian point sources. 50% of the watershed DRP load is from point sources, with 259 MTA from US point sources and 47 MTA from Canadian point sources. Wastewater treatment facilities are the largest point source, with industrial facilities such as food processing and metal finishing plants contributing smaller amounts. The WRRF is one of the largest wastewater treatment facilities in the world, treating sewage from 3 million residents across 77 communities. It also handles stormwater because much of the region has a combined sewer system. It contributes 23% of the watershed TP load, or 326 MTA, which is more than all other point sources combined, and more than any individual tributary. It also contributes 27% of the watershed DRP load.

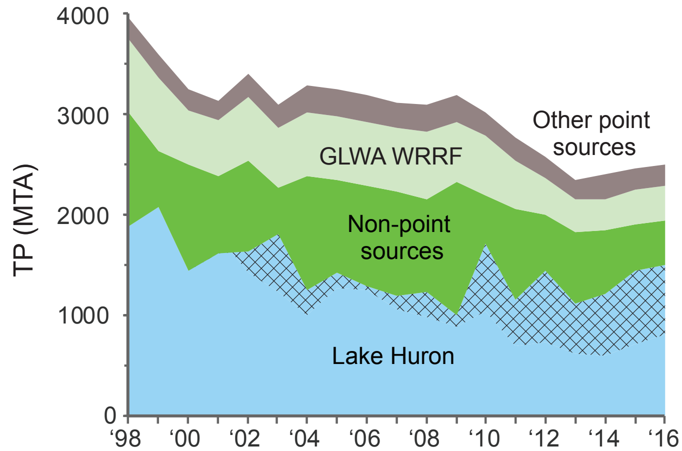

Figure 11. Time series of the total load to Lake Erie (accounting for Lake St. Clair retention, Chapter 3). Hatched lines represent the unmeasured load from Lake Huron. Available data limited the estimate for the unmeasured load to 2001-2015; here, the value for 2016 is assumed to be the same as 2015.

Detroit River phosphorus loads have declined over the past 18 years - Our analysis shows the Detroit River load declined from 3,956 MTA in 1998 to 2,502 MTA in 2016, a 37% decline over 18 years (Figure 11). **When we refer to the Detroit River load, it accounts for phosphorus retention in Lake St. Clair and it means the load from the Detroit River to Lake Erie.**

There are two primary reasons for these declines (Scavia et al. 2019): (1) The concentration of phosphorus in Lake Huron water declined after the 2000-2005 invasion of zebra and quagga mussels, which are voracious filter feeders and concentrate nutrients in their bodies along the lake bottom, and during a period of particularly low lake levels; and (2) The Detroit Water and Sewerage Department made significant improvements to operations at its wastewater treatment facility (now called the GLWA WRRF) around 2010. Nonpoint source loads are influenced by precipitation patterns, land management, and land use, and they did not show a statistically significant trend over this time period.

SUMMARY

Analysis of data from US and Canadian long-term river monitoring programs and point sources outlines the sources of Detroit River phosphorus loads and indicates that the load has declined by 37% since 1998 and by 19% since 2008. Lake Huron contributes slightly more than half of the Detroit River load, higher than prior estimates. The new estimates are derived from accounting for currently unmeasured loads that appear to be driven by shoreline erosion and resuspension of sediment in southeastern Lake Huron during periods of high winds and waves. This unmeasured load has been increasing due to reduced ice cover and increased storms and waves in Lake Huron. After Lake Huron, the largest contributors are the Water Resource Recovery Facility in Detroit and Canadian agricultural runoff.

This analysis provides the backdrop for assessing potential approaches to reduce phosphorus that enters Lake Erie from the Detroit River. After an analysis of the effect of Lake St. Clair on loads from its tributaries and the St. Clair River (Chapter 3) and an assessment of urban sources (Chapter 4), Chapters 5 and 6 evaluate a series of options for reducing those loads, and Chapter 7 provides an overall summary.

3 NUTRIENT PROCESSING IN LAKE ST. CLAIR

In contrast to the Great Lakes proper, Lake St. Clair is small (1,115 km^2, 4.3 km^3) and shallow (mean depth about 4 m; Figure 12), with a short water residence time (~9 days), and the largest ratio of watershed to lake surface area (13.5:1). Its watershed is one of the most densely populated in the Great Lakes region, and it is an important source of drinking water, commercial and sport fishing, and other forms of recreation.

The lake processes water and phosphorus from lakes Superior, Michigan, and Huron via the St. Clair River, as well as from its proximate 15,000 km^2 watershed that is roughly 63% in Canada and 37% in the United States. It receives phosphorus from many tributaries, the most significant being the Clinton, Thames, and Sydenham rivers, as well as from point sources that discharge directly into the lake. While the lake's overall flushing time is roughly nine days, water in the southeastern part of the lake flushes more slowly than water in the northwestern part during summer. This, in combination with different timing and magnitude of tributary loads, leads to relatively low algal production in the northwest and higher production in the southeast parts of the lake.

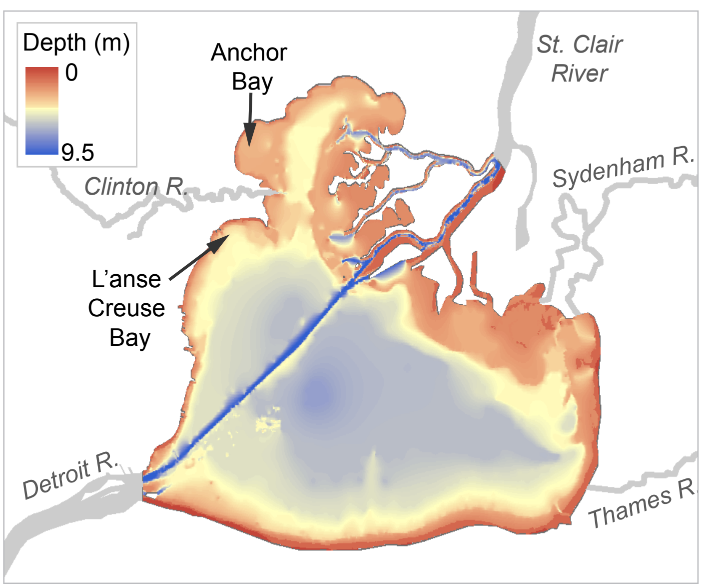

Figure 12. Map of Lake St. Clair showing depth and major tributaries.

RESULTS AT A GLANCE

- On average, Lake St. Clair retains 20% of the TP but much less of the DRP that enters the lake annually.
- Retention is likely caused by a combination of uptake by mussels and plants and sedimentation in deeper parts of the lake.
- Lake St. Clair is shallow but not well mixed, and high flows from the St. Clair River pass quickly through the lake via a deep navigation channel.
- The TP and DRP inputs from different tributaries are processed and retained differently depending on lake circulation patterns and differences in the timing of high nutrient loads.
- TP and DRP loads from the Thames have lower retention rates in the lake compared to the loads from the Clinton and Sydenham, so load reductions in the Thames will result in larger reductions at the outlet of Lake St. Clair.

APPROACH

To estimate Lake St. Clair's phosphorus retention rates, we used two approaches. The first one was based on annual inputs and outputs for 2001-2015 as described in Chapter 2. The second approach explored retention at smaller spatial and temporal scales with a calibrated and validated three-dimensional ecological model[6] that simulates nutrient and plankton dynamics at daily scales for 2009 and 2010. While the analysis for 2001-2015 generated annual retention estimates, it was only possible to run the ecological model for the ice-free March-November period. This ecological model was also used to explore the relationship between major tributary loads and loads leaving the lake.

Most of the material in this section draws from three publications: "*St. Clair - Detroit River System: Phosphorus mass balance and implications for Lake Erie load reduction, monitoring, and climate change*" by Scavia et al. (2019); "*Nutrient*

[6] Our fine scale Lake St. Clair simulations are based on a widely used coupled modeling tool known as the Estuary, Lake and Coastal Ocean Model (ELCOM) and the Computational Aquatic Ecosystem DYnamic Model (CAEDYM). ELCOM is a 3D hydrodynamic model that serves as the hydrodynamic driver for CAEDYM, a model capable of simulating a wide range of ecological processes and state variables.

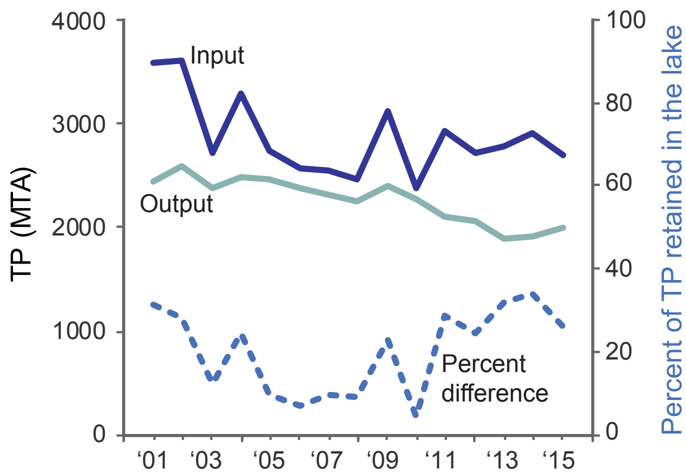

Figure 13. Input (solid dark blue), output (sage), and annual retention of TP (blue dashed; right y-axis) for Lake St. Clair.

loss rates in relation to transport time scales in a large shallow lake (LSC, USA – Canada): insights from a three-dimensional lake model" by Bocaniov and Scavia (2018); and "On the role of Lake St. Clair in modulating phosphorus loads to Lake Erie" by Bocaniov et al. (in review).

LAKE ST. CLAIR IS A TP SINK

To determine if Lake St. Clair is a net source or sink of phosphorus, we constructed annual total phosphorus (TP) and dissolved reactive phosphorus (DRP) mass balances for the entire corridor (Scavia et al. 2019) (Figure 4) for the period 1998-2016. Calculating the annual TP retention as the sum of all of the lake's inputs minus its outputs, divided by the inputs for each year, indicated that, on average, the lake retained 20% of its TP inputs (Figure 13). While measurements of DRP are less reliable, it appears that its annual retention is much less, perhaps approaching zero.

We also calculated seasonal TP and DRP retention rates with the ecological model by subtracting the sum of all of the modeled daily outputs from the sum of the daily inputs, divided by the sum of the inputs. The results indicated that, for the simulation period of March through October, 17.3% of the TP was retained and 34.8% of the DRP was retained. This seasonal TP retention rate is slightly lower than the one based on annual data because the model could only run for the ice-free season, and ice cover would increase retention. The model's high seasonal DRP retention is likely because DRP is rapidly taken up by algae, adding to the overall retention.

To the extent that the annual DRP retention rate is accurate, it suggests that much of the DRP retained during the growing season is recycled back into the water and exported during the colder months.

What causes the retention? - Scavia et al. (2019) suggested that the introduction of zebra and quagga mussels in the 1980s could have contributed to the sequestration of phosphorus into the bottom sediment. Nalepa et al. (1991) estimated that the mussel-related TP retention between May and October represented about 8.6% of the external TP load during the same period, but because the study was done prior to the zebra and quagga invasion, they suggest that value is likely an underestimate. Lang et al. (1988) estimated macrophyte growth to be roughly 7% of TP loads. So, together these could account for much of the retention. However, our work showed that physical processes are also important.

It has generally been assumed that long-term physical deposition of sediments is unlikely in Lake St. Clair because it is shallow and subjected to wind-waves and resuspension. However, we showed that wave-induced bottom shear stress (the driver of sediment resuspension) is not strong enough to resuspend sediments in the 30% of the lake that has depths greater than 5 m. So, deposition of sediment in those areas is also a likely contributor to phosphorus retention. In addition, by running our model with a range of measured meteorological conditions we found that both TP and DRP retention rates are correlated negatively with average wind speeds, suggesting that wind-dependent resuspension in the other 70% of the lake could explain why there was much year-to-year variability in retention estimates from the mass balance approach (dashed blue line, Figure 13).

LAKE ST. CLAIR OUTLET PHOSPHORUS IS MORE RESPONSIVE TO THE THAMES LOAD

While it is common to assume that nutrient loads from different tributaries are well mixed and contribute proportionally to the load leaving the lake, our study illustrated that spatial and temporal differences in loading are important and impact the influence of tributaries. We developed load-response curves that describe how the load leaving Lake St. Clair would change if the load from one of the tributaries changed (Figure 14). These not only provide insight into how changes in tributary load will influence the

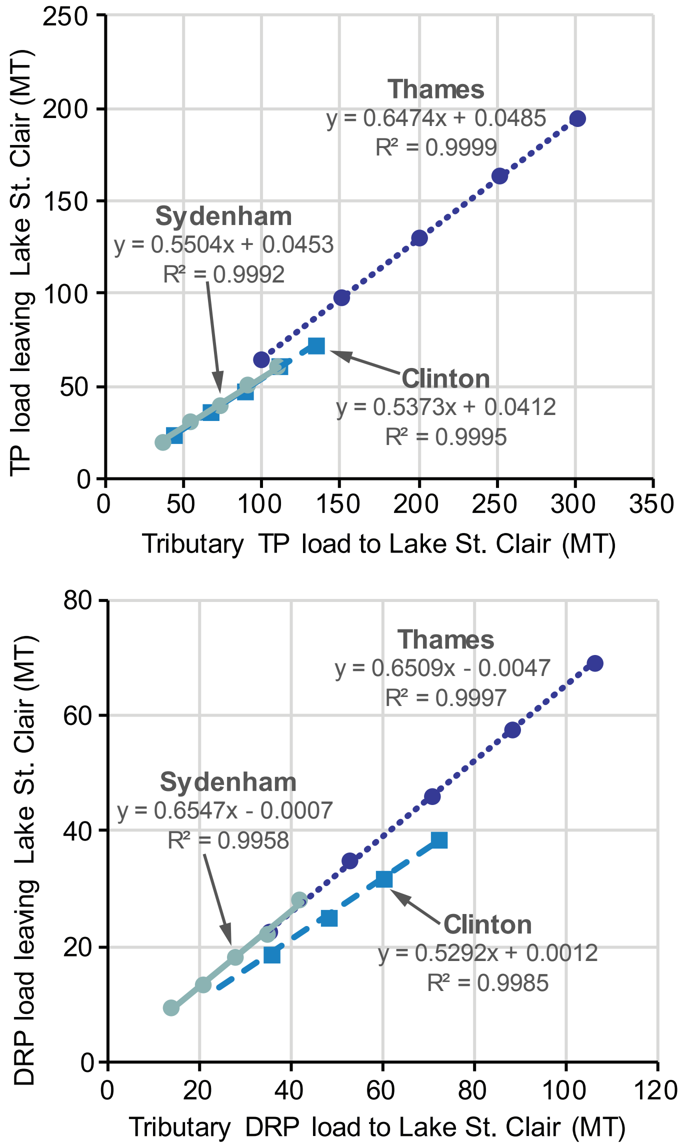

Figure 14. Relationships between tributary loads entering and leaving Lake St. Clair. Regression intercepts were subtracted from the load leaving Lake St. Clair.

outlet load, but also allow comparisons among tributaries and with the St. Clair River.

We found that within the range of 50% to 150% of typical loads, the lake's response was proportional to changes in tributary loads (Figure 14). This linear response could indicate the absence of strong in-lake feedbacks on nutrient dynamics, but it could also be because the range we tested was small relative to the lake's total load (about 70% of the load comes from the St. Clair River). The average baseline load leaving Lake St. Clair was 1,597 MT, so 50% tributary reductions, for example, would reduce the load leaving the lake by less than 5%. However, it is still important to explore the differences among these tributaries because the Thames River is called out for load reductions in the Canada-Ontario domestic action plan, and all of the loads have implications for Lake St. Clair water quality.

The slopes of the response curves represent the relative efficiency by which changes in tributary loads translate into load changes at the lake outlet. The TP response curves had slopes of 0.65 (Thames), 0.55 (Sydenham), and 0.54 (Clinton), and the DRP response curves had slopes of 0.65 (Thames), 0.65 (Sydenham), and 0.53 (Clinton). Comparing these slopes suggests that a unit reduction in the Thames load produces a larger reduction in the TP load leaving the lake than do unit changes in the Sydenham or Clinton loads. Similarly, unit reductions in the Thames and Sydenham are more effective than the Clinton at reducing the DRP load. These differences can be explained by patterns of lake circulation and resuspension and differences in the timing of the nutrient loads.

Thames - The Thames River phosphorus load is transported along the shallower east and southeast shore where it, along with resuspended material, moves toward the lake's outflow. In addition, the Thames load is largest in late winter, early spring, and late fall (Figure 15), coinciding with circulation that favors flushing and shorter river water residence times (~11 days). In late spring and summer, after most of the Thames phosphorus load has entered the lake, Thames water residence times increase to 30 - 40 days.

Sydenham - While the Sydenham and Thames river flow are similar, and the slopes of their DRP loads curves are similar, the TP slopes differ. The Sydenham is located much farther from the lake outlet (Figure 12) and separated from it by a basin deep enough (≥ 5 m) to support sediment accumulation. This enhanced particulate phosphorus retention results in higher TP retention. The presence of the deep basin, however, would not affect DRP dynamics. Because both rivers have similar hydrographs and short residence times in spring (~11 days) when their DRP load is highest and phytoplankton growth is limited (Figure 13), DRP is quickly flushed from the lake resulting in similar load-response slopes.

Clinton - Clinton River TP and DRP load-response curves have smaller slopes than the Thames, indicating larger portions of both are retained by the lake. The Clinton River load is more evenly distributed over the year, therefore, a substantial

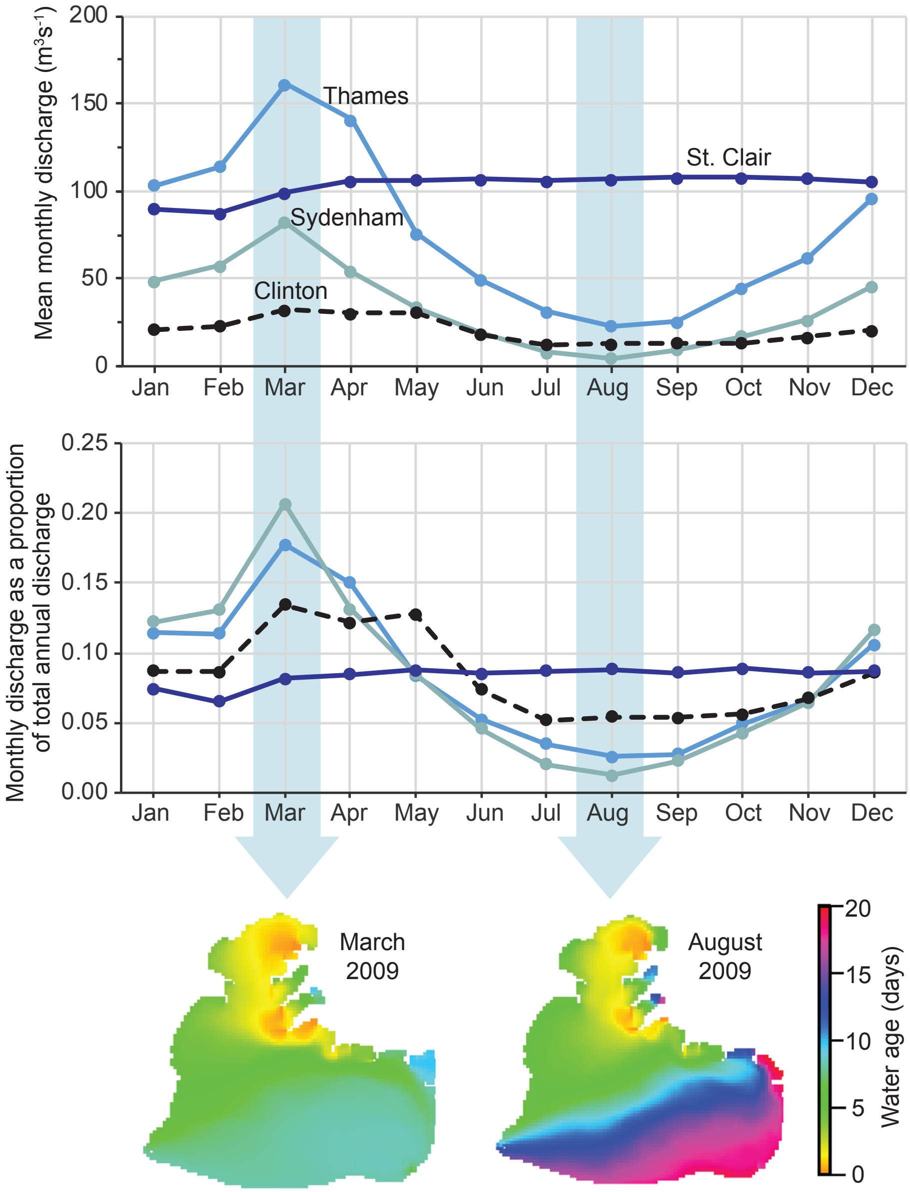

Figure 15. *Top:* Mean monthly discharge from the three major tributaries and the St. Clair River. *Middle:* Monthly discharges as a proportion of total discharge. *Bottom:* Spatial distribution of water age for March and August showing the older water (slower flushing) in the south and southeast during August. Note: the location of the river mouths are shown in Figure 12.

amount of it is delivered during periods of higher production and settling, leading to higher nutrient retention rates. The Clinton River water mass also mixes over a larger area, allowing TP settling not only in the naturally deeper parts of the lake but also in the deeper, ~8.4 m navigational channel[7]. The load can also be advected to Anchor Bay or L'anse Creuse Bay and be trapped there (Figure 12).

SUMMARY

Lake St. Clair is a net sink for phosphorus. Our long-term study indicated that the lake retains 20% of its TP input, but DRP retention is likely much lower than that. While the introduction of zebra and quagga mussels and the production of macrophytes could account for much of the retention, sediment accumulation is possible over 30% of the lake. Wind-induced resuspension over the remaining 70% could explain the year-to-year variability.

Due to the lower retention rates of flows and sediments entering Lake St. Clair from the Thames River system, changes in the Thames River load is likely to result in larger changes in the load leaving the lake compared to the Sydenham and Clinton river loads, but those changes are likely to be small compared to the overall load to the lake that is dominated by the St. Clair River.

[7] For example, in 2019 a company has been commissioned to remove almost 108,000 metric tonnes of sediments from Lake St. Clair channels.

4 URBAN SOURCES ASSESSMENT

The St. Clair-Detroit River system watershed includes 20% urban area, covering over 3,808 km^2, so it is important to consider urban inputs. Most of the information in this chapter comes from the journal article "*Total Phosphorus Loads from Urban Areas to the St. Clair-Detroit River System*" by Hu et al. (in review).

RESULTS AT A GLANCE

- London, Windsor, and Michigan urban areas together account for 24% of the Detroit River's TP load to Lake Erie.
- Urban TP loads come from point sources (80%), runoff (10%), treated CSOs (7%), and untreated CSOs (2%).
- The GLWA WRRF is by far the largest point source in the watershed and has made significant improvements in operations, reducing its dry and wet weather loads by 44.5% since 2009.
- The treated and untreated combined sewer overflow events are small fractions of the Detroit River load, but can present public health risks and other issues.

APPROACH

To delineate urban study areas, we used land cover data from the US Department of Agriculture[8] and Agriculture and Agri-food Canada[9] to select subbasins (HUC-12) with more than 80% urban land cover in the United States and more than 60% in Canada. This resulted in study areas around Detroit, MI, London, ON, and Windsor, ON, and ensured that we also included urban areas outside of the cities' political boundaries (Figure 16). The Michigan urban study area (Study Area B, Figure 16) covered 2,390 km^2 with a population of over 3.1 million people, while Windsor and London areas were 149 km^2 and 138 km^2, respectively, and had populations of 211,000 and 366,000 people.

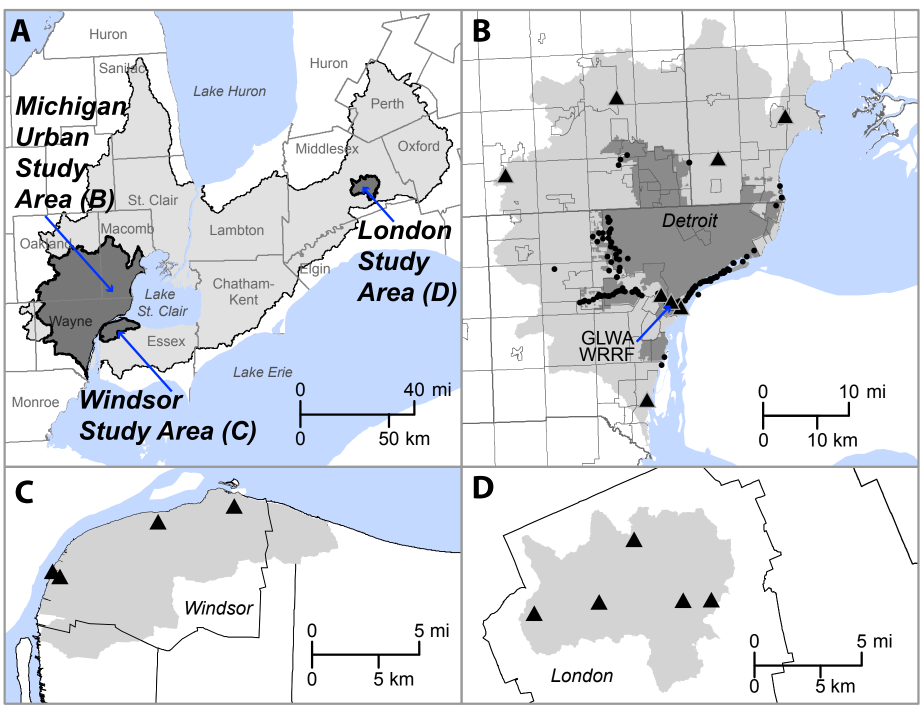

Figure 16. (A) Areas considered for this analysis of urban sources (dark gray). (B) Michigan urban study area (lighter gray) and the combined sewer area (darker gray). (C) Windsor study area. (D) London study area. Triangles are point source facilities and circles are CSO outfalls.

We considered three primary sources of phosphorus in the urban study areas: point sources, such as wastewater treatment plants[10] and industrial facilities, combined sewer overflows (CSOs), and runoff. We quantified phosphorus loads from these sources for each of the three urban study areas. Point source and CSO totals are based on measurement data from US and Canadian government agencies (details

[8] Data are from the USDA National Agricultural Statistics Survey 2016 Cropland Data Layer. Retrieved from https://www.nass.usda.gov/Research_and_Science/Cropland/SARS1a.php

[9] Data are from the Annual Crop Inventory 2011. Retrieved from https://open.canada.ca/data/en/dataset/ba2645d5-4458-414d-b196-6303ac06c1c9

[10] Phosphorus is fairly concentrated in human waste, and toilet flushing is the primary source of P in sewer water. Wastewater treatment facilities process and remove phosphorus and other contaminants, but some phosphorus remains in the discharge from nearly all wastewater facilities in use around the Great Lakes.

of data sources are in report supplemental information), and phosphorus from runoff was calculated based on precipitation and impervious area. Wet-weather discharges that occur at point sources were considered as part of the point source. Because of data availability, loads reported in this chapter are averages from 2013-2016 for point sources and CSOs, and from 2013-2015 for runoff.

Point sources, CSOs, and runoff in the three urban areas contributed 583 MTA of phosphorus, which is 42% of the watershed TP load (i.e., the load excluding the contribution from Lake Huron) and about 24% of the Detroit River's load to Lake Erie. The Michigan urban study area contributed an average of 515 MTA per year which is 88% of the total urban load and 21% of the Detroit River load. Windsor and London regions contributed 30 MTA and 39 MTA per year, respectively, which combined is about 12% of the urban load and less than 3% of the Detroit River's load to Lake Erie. Point sources contributed most of the load in all three areas (Figure 17).

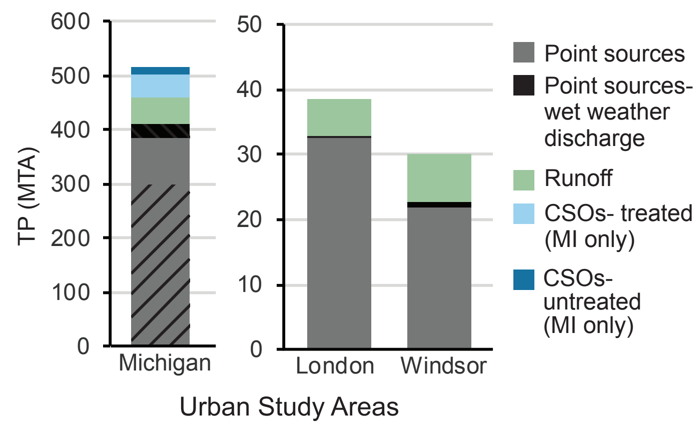

Figure 17. TP contributions from the Michigan, London, and Windsor study areas. Note the different scales on the y-axes. Diagonal lines on the point source category of the Detroit bar represent dry weather *(bottom)* and wet weather *(top)* discharge from the WRRF. The plain gray portion are the other point sources in the metro Detroit study area.

DETAILS OF THE MICHIGAN URBAN SOURCES

Point sources - The majority of the phosphorus load from the Michigan urban area is from the Great Lakes Water Authority Water Resources Recovery Facility (GLWA WRRF). It discharges about 326 MTA of phosphorus per year, which is about 63% of the load from our Michigan urban study area and about 13% of the Detroit River's load to Lake Erie. On average, 92% (299 MTA) of the facility's load is regular, dry-weather discharge, and the other 8% (27 MTA) is partially treated wet-weather discharge. There has been a substantial decrease in the phosphorus load from the facility since 2010 due to treatment improvements (Figure 18). The average TP concentration in dry-weather discharge was 0.67 mg/L prior to treatment improvements (i.e., over the years 2006-2010), and the recent (2013-2016) average concentration was 0.38 mg/L, far below the permitted limit which varies seasonally between 0.6 and 0.7 mg/L. The population of Detroit has decreased in recent decades, but the population within the GLWA WRRF's service area has remained relatively unchanged, suggesting that the amount of phosphorus coming into the facility has stayed constant while discharged phosphorus has decreased.

There are two outfalls at the facility used for wet-weather discharge when the facility reaches its treatment capacity. One outfall ("49A") discharges about 10 MTA and has an average TP concentration of 0.74 mg/L, and the other ("50A") discharges about 17 MTA and has an average concentration of 0.79 mg/L. The permitted TP concentration for wet-weather discharge is 1.5 mg/L. Wet weather discharge varies each year depending on rainfall; 2015 was relatively dry, and wet weather discharge at the facility was only 16 MTA (5% of the plant's load), but in 2011, a wet year, it was 92 MTA (20% of the facility's load).

There are nine other permitted point source facilities in the Michigan urban study area (listed in report supplemental information). All together, they contributed 88 MTA per year on average, which is 17% of the Michigan urban study area load and about 4% of the Detroit River's load to Lake Erie.

Combined sewer overflows - In addition to generating wet-weather discharge at the WRRF, high rainfall can also lead to combined sewer overflows (CSOs). This is because parts of the Michigan urban study area have combined sanitary and storm-water sewers (Figure 16B), and during storms volumes may exceed the system's capacity. Retention treatment basins (RTBs), also called "CSO basins," serve as wet-weather system storage and can hold back water during wet weather and then send it to the treatment facility when it regains capacity. If RTBs reach capacity, though, the diluted sewage is discharged to nearby water bodies after receiving primary treatment (i.e., settling and chlorination). These events are considered "treated CSOs." Treated CSOs also occur at three screening and disinfection (S/D) facilities which treat water but do not hold it back like RTBs. Where neither RTBs nor

S/D facilities are present, sewage can overflow as "untreated CSOs" during wet weather.

There are 26 treated and 78 untreated CSO outfalls that each had at least one overflow event during the study period. Treated CSOs contributed about 8% (41 MTA) of the Michigan urban study area phosphorus load, and untreated CSOs contributed about 2% (12 MTA)[11]. A list of all CSOs and details on their load calculations, as well as details on each individual CSO basin are available as supplemental information on the project webpage.

Runoff - Runoff from impervious surfaces in the separated-sewer portion of Michigan urban study area contributed an average of 47 MTA per year of phosphorus. We did not calculate runoff for areas with combined sewers because it is assumed that runoff there enters the sewer system and becomes part of either CSOs or discharge from the WRRF. The phosphorus load from runoff in the study area is about the same as the load from treated CSOs. However, in individual communities where RTBs are present, the phosphorus load from the RTBs could be greater than that from local runoff. For example, in the northwestern corner of the combined sewer region, there are three RTBs within two miles of each other (Figure 16B), and so surface water in that region may receive more phosphorus from the RTBs than from runoff. These loads are very small relative to the regional and watershed totals, but they may be impactful to the local water bodies and the community.

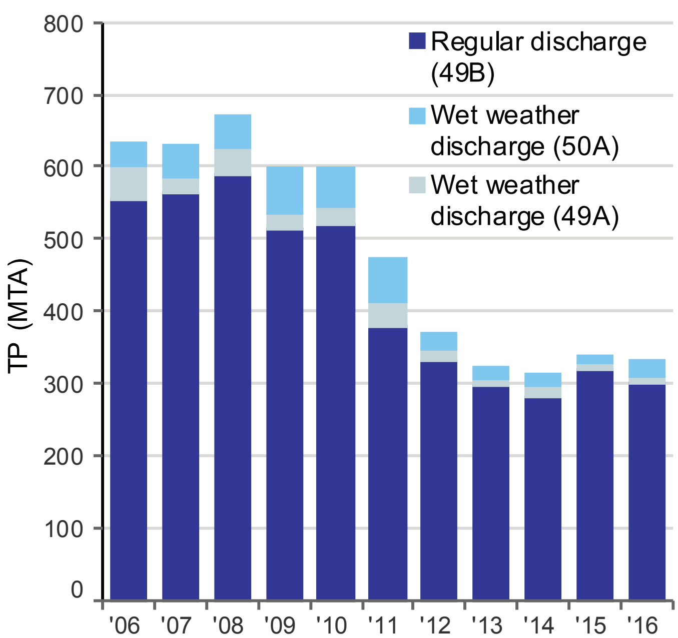

Figure 18. Annual TP loads discharged from the WRRF. The facility's dry-weather outfall, used for regular discharge, as well as its two wet-weather outfalls are shown.

DETAILS OF THE LONDON AND WINDSOR URBAN SOURCES

The relative proportions of the load from point sources and runoff in Windsor and London were similar to those in Michigan; point sources contributed the majority of the load (Figure 17). Small parts of the London and Windsor study areas have combined sewer systems, but data delineating combined and separated sewer areas were not available, and CSOs are only reported as wet weather discharges at the wastewater treatment plants. These discharges were considered as part of the point source, and no data were available for other CSOs in London and Windsor. While phosphorus inputs from these urban areas may create local issues and be associated with concerns about other nutrients or contaminates, they are relatively minor at the watershed scale.

SUMMARY

The GLWA WRRF is the largest urban source of phosphorus, representing about 63% of the load from the Michigan study area and about 13% of the Detroit River's load to Lake Erie. The other 37% of the Michigan urban area's load is divided between 9 point sources, over 100 CSO outfalls, and runoff from impervious surfaces throughout the region, so there is no other single source that makes substantial impacts on the watershed load (Figure 17). The WRRF has already reduced its load substantially from the 2008 baseline and further reductions from additional treatment technologies could be very expensive. Contributions to the Detroit River load from runoff and CSOs are relatively minor; however, efforts to reduce these can have benefits at the neighborhood level. Options for addressing urban contributions are discussed in Chapter 6.

[11] The concentration of untreated CSOs was not available, so we used the reported concentration of inflow to the GLWA WRRF (1.25 mg/L) as a conservative estimate. However, the phosphorus concentration of water discharged during untreated CSO events can vary depending on factors such as duration of discharge and antecedent conditions. Measured concentration of treated CSOs ranged from 0.11 mg/l to 18 mg/l.

5 OPTIONS FOR REDUCING LOADS FROM AGRICULTURAL SOURCES

We used the Soil and Water Assessment Tool (SWAT) to model the entire St. Clair-Detroit River System watershed and explore options for reducing total phosphorus (TP) and dissolved reactive phosphorus (DRP) loads. Most of the material in this section draws from two papers: "*Modeling flow, nutrient, and sediment delivery from a large international watershed using field-scale SWAT model*" by Dagnew et al. (2019a); and "*Modeling phosphorus loss reduction strategies from the international St. Clair-Detroit River system watershed*" by Dagnew et al. (2019b).

APPROACH

SWAT[12] is a flow and water quality model that has been used in watersheds around the world. It provides information at both coarse and fine spatial scales by dividing the individual watersheds (e.g., the Clinton, Thames) into subbasins based on topography, and then dividing the subbasins into smaller modeling units (known as Hydrologic Response Units or HRUs), based on unique land use, soil type, slope, and/or management combinations. The modeling units in our model correspond approximately to farm fields (approximately 171 acres each), the first time this has been done for a watershed of this size.

While management practice data (e.g., tillage, fertilizer application rates) are critical for estimating nutrient losses, there is not a public data source for this granularity of data at the farm level and confidentiality rules limit sharing information about individual farmers. Instead, we must rely on inputs at lower spatial resolution (e.g., county) to estimate practices at the field level. Given the variability in agricultural management between the US and Canada, we engaged the advisory group extensively over the course of two years to verify or augment available data and to collect new data where appropriate or as suggested by them. These consultations and resulting model changes are documented in our report supplemental information and our model documentation and inputs are described in the papers listed above. While we used the best available information on current practices, data limitations required us to make assumptions about current conditions at the farm scale. As a result, our analyses show changes from our estimated current condition and are illustrative of changes one might expect.

The model was calibrated (2007-2015) and validated (2001-2006) to loads estimated from measurements in five major tributaries at daily, monthly, and annual time scales, and then used to simulate loads from each of those tributaries (Figure 19). Modeling results for land management scenarios are reported for each of the major tributary watersheds, and we assumed watersheds with similar characteristics would respond similarly (see textbox "Key Characteristics of Major Watersheds" in Chapter 2). Model set-up data and assumptions as well as the calibration process are outlined in our report supplemental information.

RESULTS AT A GLANCE

- The highest TP and DRP load reductions were achieved by adding wetlands to capture flow, placing filter strips to intercept flow off fields, subsurface placement of fertilizer, and planting cover crops.
- No individual practice tested could achieve a 40% reduction alone, even if adopted on 100% of appropriate lands.
- A combination of practices adopted on 55% of crop lands with highest phosphorus loss can reduce loads by more than 40% in agriculturally-dominated watersheds.
- For agricultural areas, it is more efficient to focus practices on areas with higher phosphorus losses, suggesting the need for more data on existing management.
- The practices that meet the annual TP targets also meet spring DRP targets for the Thames River.

[12] The Soil and Water Assessment Tool (SWAT) is an open source model developed and actively supported by researchers at USDA and Texas A&M. The model is widely used to predict the water quality impacts of land use, agricultural land management practices, and climate change. To learn more, visit: swat.tamu.edu

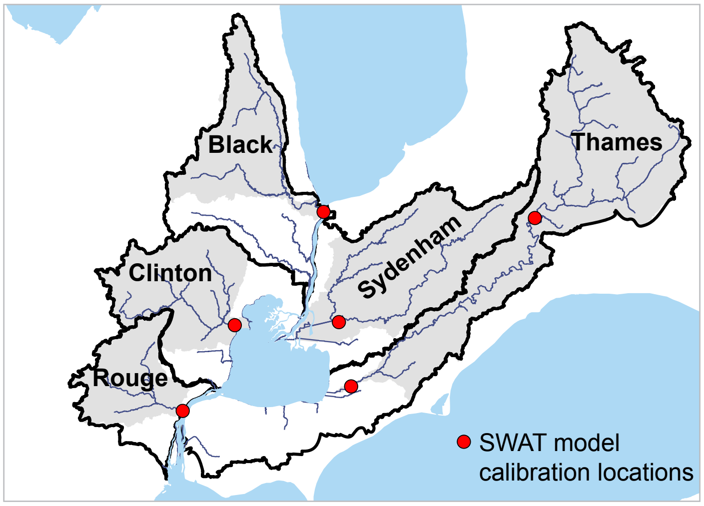

Figure 19. SWAT model calibration locations. Areas shaded gray and labeled with bold text represent the calibrated river watersheds. Calibration and scenario results for those watersheds are assumed to be representative of adjacent areas (not shaded) within the bold black lines.

Single practice model runs - We first used the model to examine the effects of implementing eight single land management practices. These initial modeling runs were tests of model performance and do not necessarily represent recommendations for real world practice. Results for modeling runs that assumed 100% adoption are presented to explain the process used to compare and select practices for use in subsequent modeling scenarios that combined several practices. For single practice runs, nutrient application practices, drainage, and cover crops were applied to all croplands; wetlands, filter strips and grassed waterways were applied to all lands, including permeable urban areas.

Multiple practice model runs - We developed five bundles of two or three management practices based on knowledge of the practices and recommendations from our advisory group. Each bundle was evaluated under three adoption strategies: (1) applied to all appropriate land[13], (2) applied randomly to 55% of the appropriate land, and (3) focused on the 55% of the appropriate land with high TP or DRP loss yields. Combinations of practices were applied simultaneously to the same field units to control different pathways of nutrient loss.

RESULTS FOR SINGLE PRACTICE MODEL RUNS

No individual practice was sufficient to meet the targets -

Wetlands, filter strips, nutrient application rate reductions, subsurface nutrient placement, and cover crops all reduced TP and DRP loads from the agriculture-dominated watersheds (Figures 20-22). DRP was more responsive to the fertilizer reduction scenario because fertilizer dissolves and moves through the soil through macropores to drainage tiles in clay soils. For all other single practice scenarios, TP was slightly more responsive than DRP because most conservation practices target surface losses by trapping phosphorus adhered to sediment. Given these practices were primarily applied to agricultural fields, there was little change for watersheds dominated by urban and suburban areas (Clinton and Rouge). However, none of the practices implemented alone achieved a 40% load reduction for each watershed, even when simulated on 100% of appropriate land.

Next we describe modeling results for individual practices, beginning with the five practices that showed promising results for reducing both TP and DRP and were used in bundled scenario runs. It is important to note that in the real world and within watershed models, the effectiveness of a individual practice depends on exactly how it is implemented and conditions on a particular field.

Reduced nutrient application rates (Rate) - Nutrient application rates under baseline model conditions were calculated based on data about fertilizer sales and animal counts in a county or province as well as the crop rotation simulated on a field. Single practice modeling runs evaluated

Nutrient application

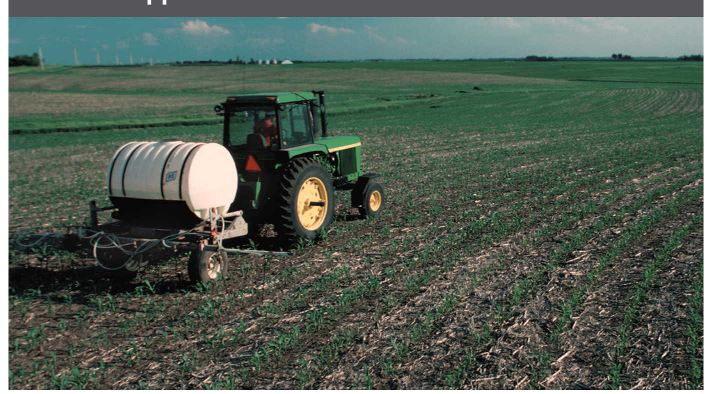

Photo credit: Lynn Betts, USDA NRCS

[13] Here, and throughout this chapter, "appropriate lands" are lands where a practice can be implemented. For example, cover crops (CC) , subsurface placement (PL) and fertilizer reduction (rate) can only be implemented in croplands while WT can be implemented for any land use type.

the impact of reducing nitrogen and phosphorus inputs from fertilizers and manure simultaneously with different levels of reduction. We found that loads responded as expected to reductions in nutrient application rates (Figure 20), with larger reductions in the Sydenham compared to the Thames. The Black watershed showed smaller load reductions, most likely because its baseline phosphorus loads were already much lower.

Our modeling analyses showed that a 25% reduction in nitrogen and phosphorus inputs, implemented simultaneously over a fifteen year period, led to ~10% reduction in corn yields, ~3% yield reduction for wheat and no change for soybeans on average. Impacts of reducing phosphorus inputs alone were not evaluated and may have had a smaller impact on crop yields. Potential impacts on crop growth will vary based on crop type and field conditions. Farmers considering this practice can use soil phosphorus testing to determine crop needs and assess whether a specific fertilizer reductions would reduce yield.

Subsurface placement of nutrients (PL) - Subsurface placement is the practice of placing nutrients into the soil instead of leaving them on the soil surface. We assessed the impacts of switching from surface application prior to tillage to subsurface placement, including both inorganic P and N inputs from fertilizer and manure, without any change to a field's assumed tillage style (i.e., no-till, conservation or conventional, depending on field). We found that phosphorus loads responded roughly linearly as we increased the fraction of nutrient additions placed in the soil. When 80% of the nutrients were placed in the subsurface, both TP and DRP loads were reduced by roughly 34% for the Sydenham and 30% for the Thames watersheds (Figure 21). Both nutrient management scenarios (rate reductions and subsurface placement) generated only small reductions in TP and DRP yields from the Black River.

Subsurface nutrient placement

Photo credit: Jordan Hoewischer, Ohio Farm Bureau Federation

Once incorporated, nutrients are less likely to run off a field and can lead to more efficient use by crops. This practice can be achieved by applying fertilizer just prior to planned tillage; strip tilling with fertilizer; or through banded-placement either in the row as starter for seeds or with a low-disturbance banded applicator. Specialized equipment is often required for this practice.

Filter strips (FS) - We simulated the potential impact of adding filter strips that cover 1.7% of a field, for all permeable lands. For this scenario in SWAT, half of the field area drained to the filter strip and runoff from the rest of the field area was not impacted by the practice. Modeling results found that adding filter strips reduced 20% to 39% of TP and 18% to 37% of DRP (Figure 21). TP and DRP reductions were similar in watersheds with relatively low nonpoint source loads (Black, Clinton, Rouge), but it appears that watersheds with higher

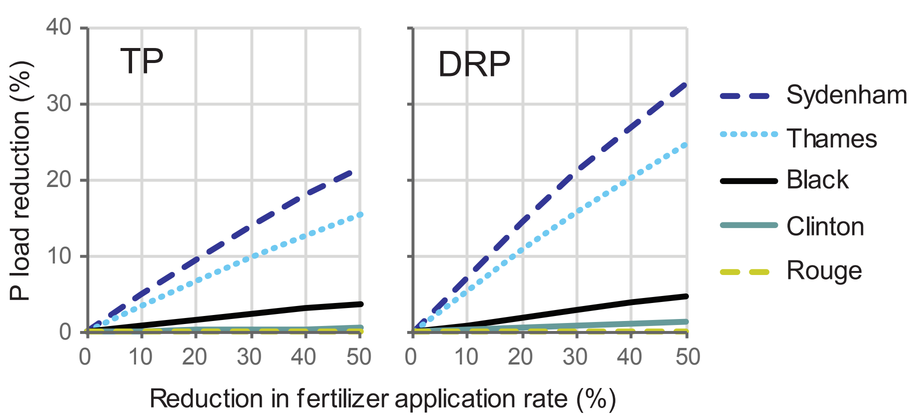

Figure 20. Percent reductions of TP and DRP resulting from reducing fertilizer application rates.

Filter strips

Photo credit: Minnesota Pollution Control Agency

nonpoint source loads (Sydenham and Thames) may need larger or more effective filter strips.

Filter strips, also known as buffer strips, are areas that are planted with grasses and other non-woody vegetation. They are typically placed along the downstream edge of a field or along a waterway to intercept surface runoff and allow soil particles to be deposited. This practice requires taking land out of production and the loss of productivity for a farmer can be costly. Careful site assessment and placement are required for filter stips to be most effective. This practice is typically found to be more effective at reducing losses of TP than DRP.

Cover crops (CC) - This scenario evaluated the impact of planting cereal rye as a cover crop in the fall in fields dedicated to corn and soybeans. Modeling results found that cover crops reduced TP loads by 30% and 23% and DRP loads by 24% and 18% for the Sydenham and Thames watersheds, respectively (Figure 21), but reductions were less than 6% in the Black, Clinton, and Rouge watersheds. Field research on cover crops indicates that effectiveness varies depending on how the practice is implemented and the species used. We tested other cover crop species in SWAT with very similar results.

Cover crops protect the soil and reduce wind and water-driven erosion during months when a field might otherwise be bare and can improve soil health over time. The use of cover crops should not impact crop yields, but there are costs for the farmer, including buying and planting seeds and potentially terminating a cover crop that survives the winter. Getting cover crops sufficiently established before winter is particularly challenging in colder climates and after crops that are harvested late in the season, such as corn and soybeans grown in Ontario. Cover crops can be seeded prior to harvest of cash crop, but this requires special equipment and is not seen as economically feasible.

Cover crops

Photo credit: Jordan Hoewischer, Ohio Farm Bureau Federation

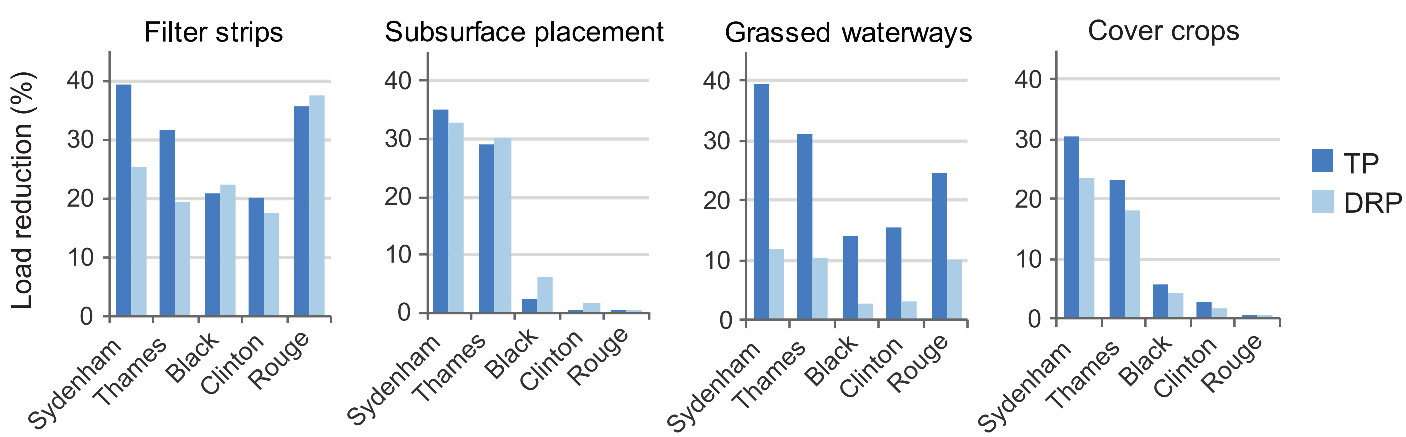

Figure 21. Percent reductions of TP and DRP in each watershed for single practice scenarios implemented with 100% adoption.

Wetlands

Photo credit: Colleen Long

Wetlands (WT) - We simulated the impact of creating wetlands of different sizes and tested the impact of varying the amount of the subbasin that drains to the wetland area. This practice was applied in both urban and rural sub-basins in SWAT. Modeling runs that assumed wetlands covered 1% and drained 50% of the subbasin area reduced TP loads between 12% and 28% (Figure 22), and except in the Black, DRP reductions were similar. Increasing the coverage of wetlands to 2% of each subbasin's area further reduced TP loads by 4-10% when 50% of the area was drained through the wetlands. DRP load reductions were similar except there appears to be a saturation point above which there was little reduction. The Black River watershed even showed an increase in DRP load if more than 20% of the area drained into the wetlands.

This practice involves creating more wetland area across a watershed through wetland restoration or construction to provide specific ecosystem services. As runoff enters a wetland, sediment settles out and wetland plants naturally absorb and process dissolved nutrients. To achieve this scenario, sites for wetland creation may need to be purchased to get enough land in the right places to capture sufficient flow, and wetland areas may need to be excavated and planted.

Grassed waterways - For this model run, we added **grassed waterways** that were as long as one side of each modeled field unit, with an assumed average width of 30 feet, depth 4.7% of the width, and a slope 0.75 times the field's slope. We found that grassed waterways were as effective as filter strips at reducing TP, but they were much less effective at reducing DRP (Figure 21). Given the need to reduce both TP and DRP, filter strips are preferred to grassed waterways, though neither can capture DRP that infiltrates and is subsequently routed through tile flow.

A grassed waterway is a natural or constructed vegetated channel that is shaped and graded to carry surface water slowly to reduce erosion. They are typically created within a field in an area where gullies tend to form after big rain storms

Controlled drainage - We simulated controlled drainage by reducing tile depth by 50% for mid-June through September and 75% for November through March. Model runs found that this scenario increased both TP and DRP loads in all cases, with the largest increase in the Sydenham (7.5%). This is consistent with a recent field scale study near the upper

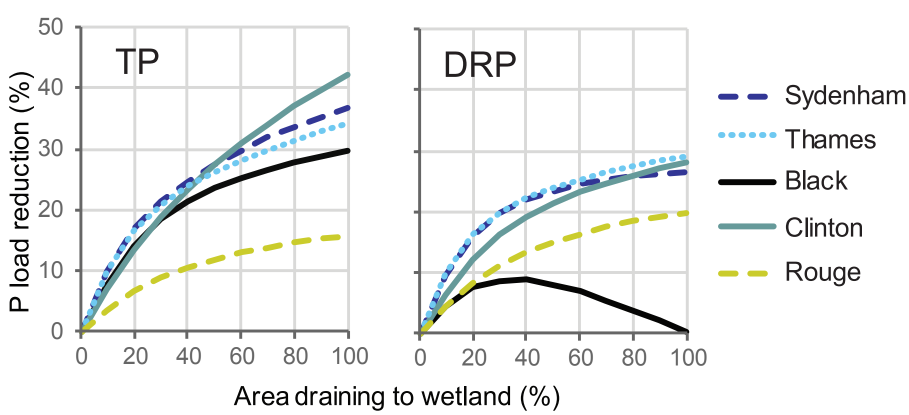

Figure 22. Percent reductions of TP and DRP resulting from increasing the area draining to wetlands in each subbasin. While the area draining to the wetland increased, the area of the wetland itself was kept consistent, covering 1% of each subbasin.

Thames (Hanke, 2018); however, there is some evidence that combining controlled drainage with cover crops may reduce overall phosphorus loss (Zhang et al. 2017).

Controlled drainage involves adjusting the outlet of a tile drainage system to control the volume of water leaving the field, store water for crop use, and reduce nutrient losses. It has been found to be effective for reducing nitrogen losses from a field, but the impacts for phosphorus control are less clear. Field research on this topic is on-going and can be used to improve modeling simulations and refine practical guidance for when and how tile drain flow could be managed to reduce nutrient losses.

Tillage - We evaluated the potential impact of increasing conservation tillage and no till, relative to baseline conditions that assumed a mix of tillage practices across the watershed. Given that the baseline model included all three types of tillage practices -- conventional, conservation, and no-till -- applying one type of tillage across an entire watershed had minor effects. Conservation tillage reduced TP load by about 2.6% for Sydenham and Thames, but had no effect on TP in the other watersheds or on DRP in any watershed. In our model, greater adoption of no-till practices increased TP and DRP by up to 2.6% and 5.3%, respectively.

Tillage is traditionally done to prepare a seed bed for planting. Many farmers have reduced the frequency, depth and intensity of tillage and have significantly reduced soil erosion and transport of sediment-bound phosphorus into rivers. Our baseline model assumed surface application of nutrients and without any tillage a field can be susceptible to surface losses over time (Jarvie et al. 2017). Combining no-till with side-casting or subsurface nutrient placement likely would have shown different results, but this was not tested.

RESULTS WHEN COMBINING PRACTICES

Bundled practices can surpass reduction targets in some watersheds - Results of the single practice model runs identified five practices that showed good potential for reducing DRP and TP loads from watersheds with significant agricultural lands. Initial results informed the selection of specifications for subsequent "bundled" model runs that combined practices. Each of the individual practices reduced nutrient loading through a somewhat different process and therefore combining practices on specific fields was particularly effective for improving downstream water quality.

UNDERSTANDING PHOSPHORUS LOSSES FROM FARMS

Fertilizer and manure that are applied to agricultural lands can be a major source of nitrogen and phosphorus that ends up in streams and lakes, particularly in watersheds that are intensively farmed such as the Thames and Sydenham in Ontario. Most commercial fertilizers are highly soluble and nutrients on the soil surface can wash off a farm field through overland runoff or through subsurface flow paths after a storm. In lower lying areas around the Lake Erie basin, tile drains have been placed in farm fields to improve drainage and these tiles also provide a pathway for nutrient loss. Fertilizers are expensive and farmers use a variety of tools to calculate the necessary amount of nutrients for a given crop to avoid over-applying. Recent studies have indicated that the amount of phosphorus in fertilizer and manure currently being applied on fields does not exceed the amount taken up by crops, on average (Bruulsema 2016, Jarvie et al. 2017). A variety of regulations and recommendations help livestock operations avoid conditions that would lead to leaching and runoff of nutrients from manure. However, even small amounts of excess organic and inorganic nutrients can bind to soil and build up in farm fields over time. The right combination of conditions, such as a big rain event falling on exposed soil, can lead to soil erosion and the transport of both sediment-bound phosphorus and dissolved phosphorus through gullies and tile drains and into streams.

Our watershed modelling found five individual strategies were particularly effective at reducing DRP and TP losses from croplands in the Sydenham and Thames watersheds. Each of the best management practices reduced nutrient loading through a somewhat different process and therefore combining practices on specific fields was found to be particularly effective for improving downstream water quality.

Practices and specifications used in the bundled scenarios are as follows, listed in order of modeled effectiveness for reducing TP and DRP losses from agricultural lands:

- **Wetlands (WT):** We assumed that 1% of every subbasin's land area was converted to a wetland and those wetlands were positioned such that 50% of the flow in a sub-basin passed through them. This practice was applied in both urban and rural sub-basins in SWAT.
- **Sub-surface placement of nutrients (PL):** We assessed the impacts of switching from surface application prior to tillage to subsurface placement of both inorganic P and N fertilizer and manure, without any change to a field's assumed tillage style. In SWAT, field units with this practice had 80% of nutrients placed sub-surface and 20% left on the surface.
- **Filter strips (FS):** This scenario assumed 1.7% of a farm field was converted from crops to a filter strip/buffer strip.
- **Cover crops (CC):** This scenario assumed cereal rye was planted in the fall on field growing corn and soybeans.
- **Reduced nutrient application rates (Rate):** Based on tests of different rates, bundled practices scenarios assessed the impact of a 25% reduction in N and P inputs to a farm field, including both inorganic fertilizers and manure.

Five combinations of land management practices were evaluated, listed here in order of modeled effectiveness: (1) CC-FS-WT; (2) CC-PL-WT; (3) CC-PL-Rate; (4) CC-PL; (5) PL-Rate.

If bundled practices were applied on 100% of the appropriate lands, the bundle that included filter strips, wetlands, and cover

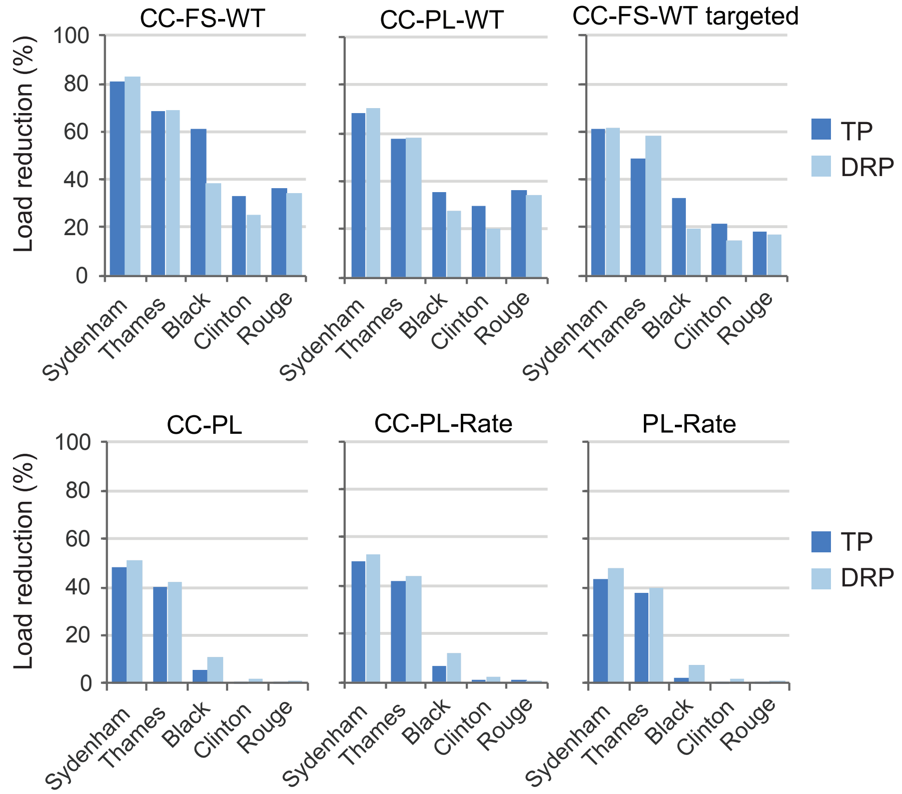

Figure 23. Percent reductions of TP and DRP for bundled scenarios. Each bundle assumes 100% implementation, except the "targeted" scenario, which places practices on the 55% of land with the highest DRP and TP yields. For bundles that altered fertilizer rates, we assumed a 25% reduction in fertilizer application rates.

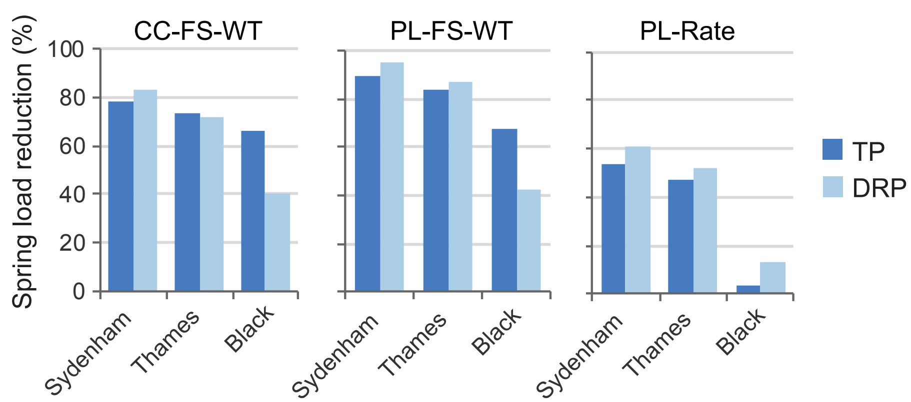

Figure 24. Percent spring (March-July) TP (black) and DRP (gray) load reductions for three bundled scenarios. Each bundle assumes 100% implementation. Compare to annual load reductions in Figure 20.

crops performed best, followed by the one that included subsurface nutrient placement, wetlands, and cover crops (Figure 23). These bundles each reduced TP and DRP loads from their watersheds by as much as 70-80%. However, several other combinations of practices could potentially achieve a 40% reduction from the agriculturally dominated watersheds (Sydenham, Thames, and Black), and some could achieve over 60% reductions at 100% adoption.

The CC-PL-FS, PL-Rate, and CC-PL-Rate bundles were effective in reducing loads by 40-50% in the Thames and Sydenham watersheds. The CC-PL bundle performed almost as well as CC-PL-Rate bundle, suggesting that it may not be necessary to reduce fertilizer application rates if cover crops and subsurface placement of fertilizer are implemented. Because fertilizer application rates in the Black were already low, these scenarios were not as effective in that watershed. Adding filter strips to the CC-PL bundle further decreased the TP and DRP loads from the Sydenham and Thames, and it was a particularly effective bundle for reducing the TP load from the Black watershed.

Because PL, Rate, CC, and FS were only implemented in agricultural areas, the two urban dominated watersheds (Clinton and Rouge) had the lowest reductions under those scenarios. However, replacing filter strips with wetlands in those scenarios resulted in significant reduction . Reducing imperviousness, as discussed below, is likely a more effective strategy for those areas (See Chapter 6).

Focusing bundled practices is more effective - Placing the practices on just the 55% of land with the highest TP and DRP loss yields also surpassed target-level reductions. For example, a 55% focused implementation of CC-FS-WT could achieve a 50% load reduction in the Sydenham sub-watersheds for both TP and DRP (Figure 23). The Thames may require slightly more than 55% to reach the same reduction levels. The results using this focused approach, coupled with the relative effectiveness of different combinations of practices, suggests there is flexibility in selecting the most effective practices across the landscape. It is important to note, however, that while our modeling approach demonstrates the benefits of focusing practices on high phosphorus loss lands, these areas will have to be identified on the ground using farm- or field-level management information (Muenich et al. 2017).

Reducing the Thames and Sydenham spring loads - While the annual TP load from the Detroit River is most important for central basin hypoxia, the binational agreement also calls for a 40% reduction in spring (March-July) TP and DRP loads for, among other watersheds, the Thames River. Therefore, we explored the impacts of key bundled scenarios on the Thames spring load. Because the Sydenham is the most agriculture-dominated watershed next to the Thames, we assessed the impact on it as well. We included the Black for comparison. We explored the CC-FS-WT bundle because it was most effective for annual TP reductions. We also looked at a bundle that replaced cover crops with subsurface placement (PL-FS-WT), and a bundle that tested fertilizer application rates and subsurface placement (Rate-PL) under the assumption that fertilizer management may be quite effective for controlling spring loads. Spring fertilizer applications were used for corn and soybeans. These comparisons all assumed 100% implementation. In all cases, the spring load reduction percentages are equal to or surpass the target annual load reductions (Figure 24), indicating that practices selected to address spring TP and DRP loads will also be effective for reducing annual TP.

COMPARING US AND CANADIAN NONPOINT SOURCES

Estimated loss of DRP and TP per acre (TP and DRP loss yields) showed that losses were generally higher in Canada than in the US, especially for DRP (Figure 25), consistent with higher DRP loads measured from the Ontario watersheds and with other recent modeling work in the Ontario watersheds. We initially believed this difference was due to higher fertilizer application rates and a higher density of tile drains in Ontario.

However, running the model with the same fertilizer application rates and tile systems in both the US and Canada did not eliminate the differences in yields (Figure 26). We therefore suggest the difference between US and Canadian yields is most likely driven by higher precipitation on agricultural lands in Ontario (Figure 26).

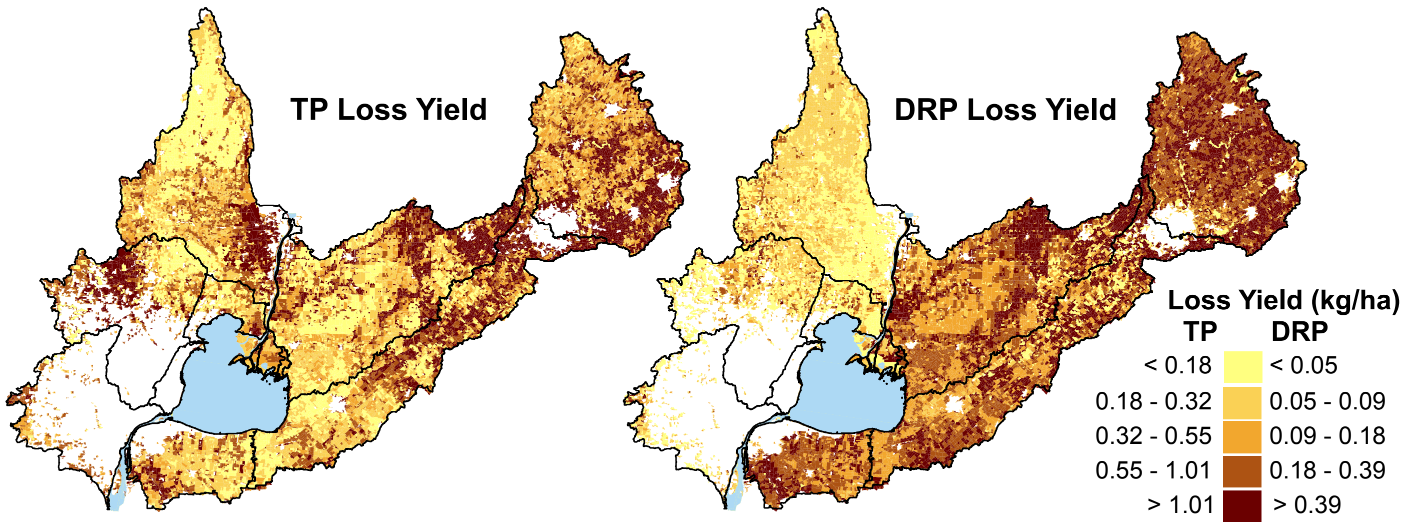

Figure 25. Modeled TP and DRP loss yields (kg/ha) for each model unit (HRU). White areas are urban land. Black lines delineate HUC-8 watershed boundaries.

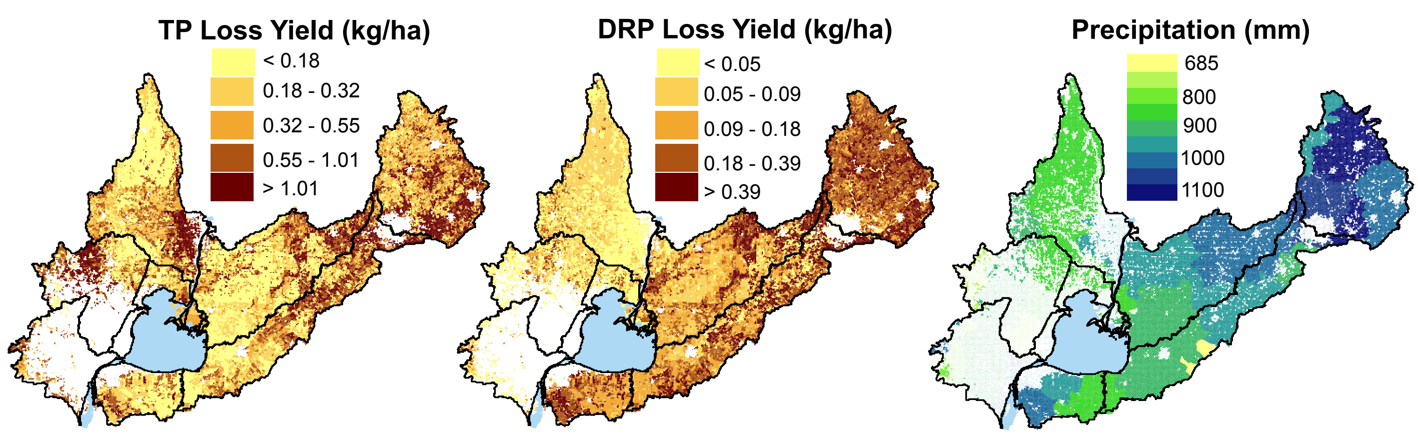

Figure 26. Modeled TP *(left)* and DRP *(middle)* loss yields assuming the same fertilizer application rates and tile system in the US and Canada. Data from urban areas *(shown in white)* are not included so comparisons can be made across agricultural lands only. Note that making these conditions the same does not remove the difference in phosphorus loss yield between the two countries. The difference is more likely driven by precipitation *(right, shown as annual average precipitation for 2001-2015).*

It appears that the differences in TP and DRP nonpoint source yields between the two countries could also be driven, in addition to difference in precipitation, by differences in soils and slopes (Figure 27). Comparing the US and Canadian watersheds to the Maumee River watershed, which delivers almost half of the phosphorus to the western basin, is informative here. While the slopes in both the US and Canadian agricultural areas are similar to the Maumee, average annual precipitation in the Maumee watershed is similar to that in the upper Sydenham and Thames, but greater than that in the US St. Clair and Detroit River watersheds. Similarly, the Canadian soils, particularly in the south-west, are largely poorly drained (group D) like those in the Maumee, but the US soils are mostly well drained (group B).

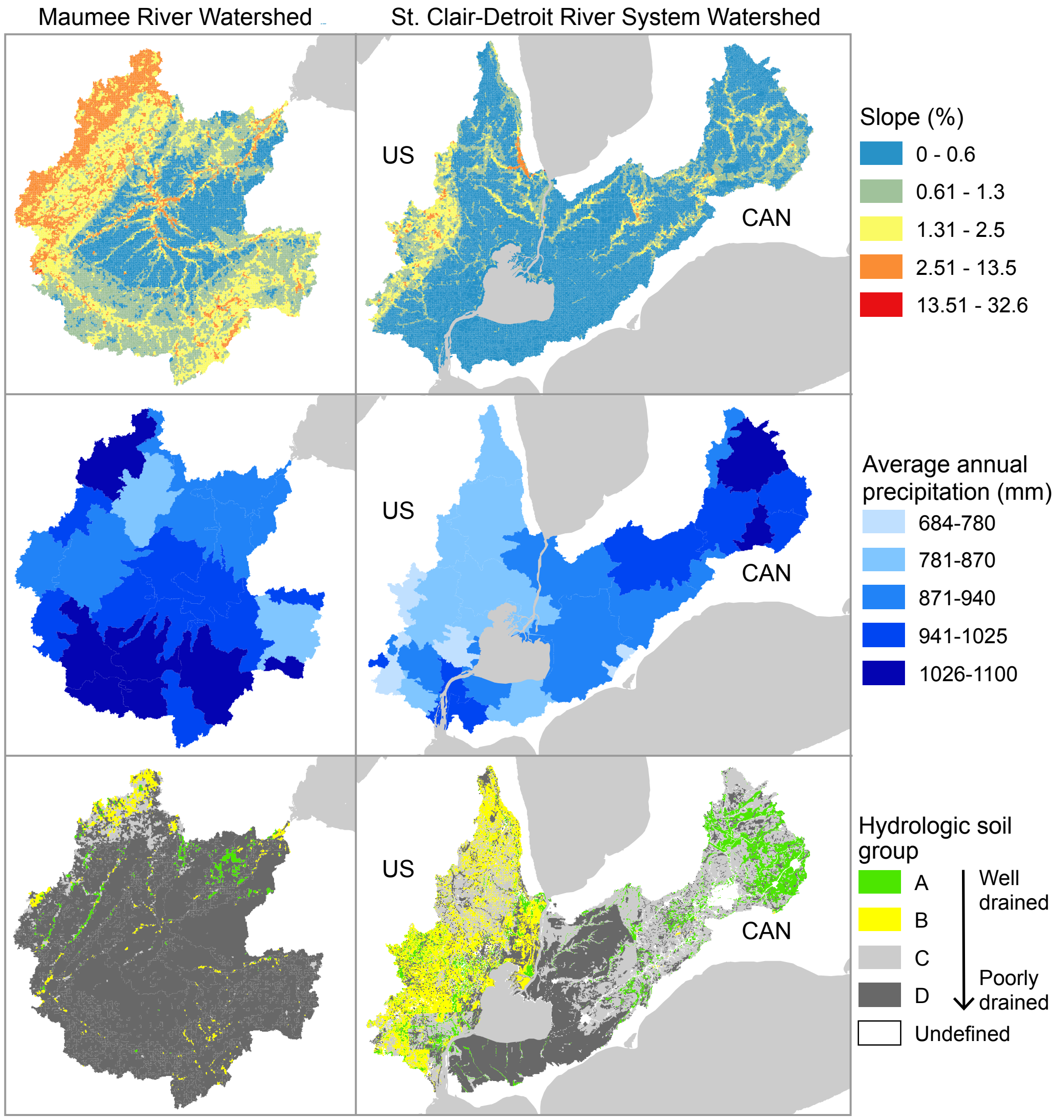

Figure 27. Slope *(top)*, precipitation (middle), and hydrologic drainage groups *(bottom)* in the Maumee River watershed (left) and the St. Clair-Detroit River watershed *(right)*. The Canadian portion of the watershed is similar to the Maumee, while the US portion has less precipitation and more well-drained soils.

SUMMARY

The SWAT analysis suggests that there are several combinations of agricultural best management practices that would be effective in reducing nonpoint source loads from agriculture, some by as much as 70-80% with a 100% adoption rate. While this scale of adoption is not possible due to real-world constraints, the analysis also suggests that focusing those same practices on 55% of the land with the highest per acre losses of TP and DRP could still achieve reductions on the order of the GLWQA targets. Similar results were seen through modeling of the Maumee River watershed (Scavia et al. 2017). For the Thames River, we found that practices that meet annual TP target of a 40% reduction, also meet spring DRP targets set for that river.

Compared to similar areas in Michigan, Ontario watersheds had higher modeled phosphorus loss yields per acre of farmland, especially for DRP, most likely because they receive more rainfall and the southwestern portion of the Ontario watersheds has more poorly drained soils.

6 OPTIONS FOR REDUCING LOADS FROM URBAN AND SUBURBAN SOURCES

INTRODUCTION

A summary of our load analysis for urban areas is provided in Chapter 4. Southeast Michigan (as defined in Figure 16B) is the primary urban source of phosphorus in the St. Clair-Detroit River system watershed, contributing 88% of the watershed's urban phosphorus load and about 21% of the Detroit River's load to Lake Erie. London and Windsor together contribute less than 3% of the Detroit River's load to Lake Erie; therefore, this chapter focuses on potential reductions in the Michigan urban area.

Quantifying the loads from point sources, combined sewer overflows (CSOs), and runoff (as was done in Chapter 4) helps indicate which sources of phosphorus could potentially be reduced and have impacts at the watershed scale, and which sources already contribute relatively small loads to the watershed. Regular, dry weather discharge from the Great Lakes Water Authority Water Resource Recovery Facility (GLWA WRRF) in Detroit contributes most of the phosphorus from the Michigan urban study area (58%; 299 MTA; Figure 17). Significant treatment improvements have already resulted in a 44.5% load reduction between 2009 and 2016 (Figure 16), and the average[14] concentration of phosphorus in the facility's dry-weather discharge is 0.38 mg/L, far below the permitted limit, which varies seasonally between 0.6 and 0.7 mg/L.

Treated CSOs from retention treatment basins and untreated CSOs are not major sources of phosphorus (contributing 44 MTA or 8.5% of the Michigan urban area load, and 12 MTA, or 2%, respectively), but reducing the amount of water they discharge continues to be a priority for local governments and NGOs because they can pollute water with bacteria, viruses, and other nutrients besides phosphorus. Furthermore, there continue to be efforts[15] to implement green infrastructure (GI) throughout the metro Detroit area for its many benefits besides water quality improvement. We therefore explored the potential for CSO reduction through green infrastructure approaches using a calibrated Storm Water Management Model (SWMM[16]) for metro Detroit and the calibrated SWAT model to examine the effects of green infrastructure across the broader urban/suburban area and on sources besides CSOs (Figure 28).

RESULTS AT A GLANCE

- On average, phosphorus sources in urban areas account for 24% of the Detroit River load to Lake Erie; 88% of that urban load comes from the metro Detroit region.
- Green infrastructure practices, including permeable pavement and bioretention cells, have more potential to reduce combined sewer overflows "upstream" (i.e., higher in the sewer system) than "downstream" (i.e., lower in the system and closer to the treatment facility).
- Downstream sewer overflows are caused by water coming from many upstream areas and thus are difficult to address through green infrastructure.
- Green infrastructure with drains often delays rather than prevents runoff from entering the sewer system. Planning should consider the timing and pattern of flows throughout the system.
- Outside of combined sewer areas, reducing imperviousness by planting vegetation has potential to reduce runoff volume and phosphorus loads.

[14] We have provided the average concentration from water years 2013-2016, which corresponds to the "current" time period used throughout this report.

[15] Information on the Detroit Water and Sewerage Department's (DWSD) green infrastructure projects is availale at https://detroitmi.gov/departments/water-and-sewerage-department/programs-and-initiatives/green-infrastructure-projects.

[16] The Storm Water Management Model (SWMM) is a widely used, open source modeling platform developed by US EPA in 1971 and is updated regularly. SWMM is a dynamic rainfall-runoff-routing simulation model that is used for single event or long-term (continuous) simulation of surface flow and subsurface transport through pipes and soil, primarily in urban contexts. It is helpful in understanding rate and timing of stormwater flows, flooding events and other rainfall-related phenomena in these urban settings

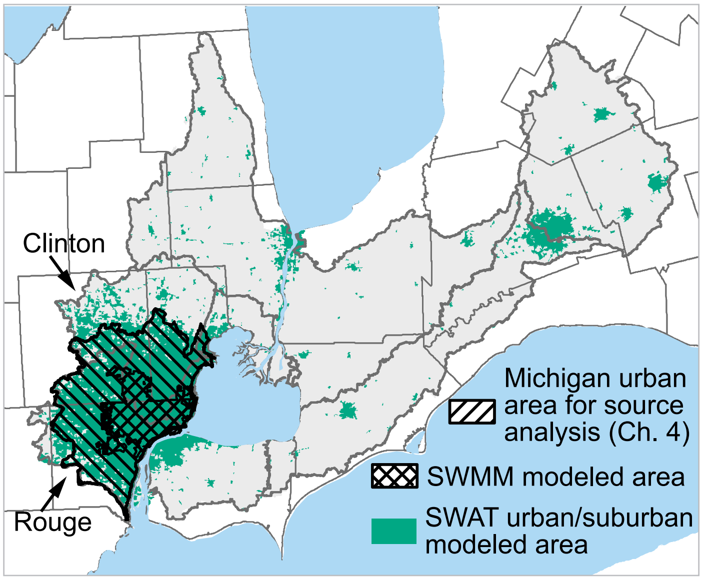

Figure 28. Study area for Michigan urban source analysis (presented in Chapter 4), the area modeled by SWMM, and the urban/suburban area modeled by SWAT. SWAT results presented in this chapter are from the Clinton and Rouge watersheds only.

MODELING APPROACH FOR SWMM

SWMM simulates the GLWA sewer service area in metro Detroit. It includes 402 subcatchments with unique land cover, soil, gray infrastructure, and connectivity to the sewer system. We calibrated the model using measurements made at 46 locations, including 33 rain gages, volumes at 12 retention basins, and inflows to the WRRF. Details on model calibration and validation are available in the article "*Are all data useful? Inferring causality to predict flows across sewer and drainage systems using directed information and boosted regression trees*" by Hu et al. (2018).

We simulated both representative rainfall conditions and an extreme storm. The representative scenario was based on the month-long period April 1-30, 2014, when about 2 inches of rain fell. The extreme scenario was based on a storm that occurred on August 11-12, 2014, when over 6.5 inches of rain fell. We simulated rainfall evenly over the system to generate comparable results for all of the modeled RTBs. Eight of the 12 RTBs did not have CSO events during the representative rainfall events, but the heavy rainfall scenario showed overflows at all RTBs in the model.

CSO contribution areas - We compiled publically available data[17] to delineate the approximate contributing areas for the retention treatment basins (RTBs) in the GLWA sewer service area (Figure 29) and then used SWMM to identify the subcatchments that contribute most to wet weather discharges. This was done by selecting subcatchments one at a time, eliminating the rainfall over that catchment, and examining the resulting percent reduction in CSOs at each outfall. This is analogous to "disconnecting" a subcatchment, which in the real world would entail converting the subcatchment to a separated stormwater system, or capturing all its runoff so that it does not go into the combined sewer system. This analysis helps provide information on how the system works and shows which areas influence wet weather discharge; complete disconnection or runoff capture may not be realistic.

For upstream retention basins (RTBs higher in the system and generally farther from the WRRF), SWMM indicated that the subcatchments adjacent to RTBs contribute most to their local CSOs. Downstream RTBs, however, receive water from multiple upstream portions of system and therefore adjacent subcatchments to the RTB are not dominantly influential to local overflows. For the wet weather outfalls at the WRRF, the model indicated that nearly all the subcatchments in the system had some influence on discharges. We normalized the CSO reduction potential of each subcatchment by its impervious area (Figure 30) as an approximation of how much wet weather discharge in the system could be reduced relatively if a unit area is disconnected from a specific subcatchment (darker regions show larger relative CSO reduction per unit area). This indicated that during an average rainstorm many of the subcatchments show a potential to reduce CSOs if disconnected. While some regions appear darker in the figure (larger disconnection potential), the contribution of any individual subcatchment is still small given the size of the service area and the total number of subcatchments.

Pervious land cover - After identifying key influential areas for each outfall, we used SWMM to estimate CSO reductions that could result from increasing pervious land cover. We calculated the fraction of pervious land cover in each

[17] Most map data comes from the Rouge River National Wet Weather Demonstration Project report available at http://www.waynecounty.com/documents/environmental/rouge_river_national_wet_weather_demonstration_project.pdf. Permits and other documents for individual CSO basins obtained from miwaters.mdeq.state.mi were also used.

subcatchment using the National Land Cover Database and then ran scenarios with perviousness increased by 5%, 10%, 15%, and 20%. These pervious cover fractions are not meant to represent realistic scenarios, but rather provide an understanding about the range of theoretical impacts that increasing pervious land has on CSOs.

Under normal rainfall conditions, increasing pervious land cover substantially reduced CSO volumes at upstream RTBs; a 5% increase in pervious cover reduced those CSOs by an average of 20%. However, impacts at downstream RTBs and the WRRF were limited. Under the extreme storm scenario, increasing the amount of pervious land by 5% resulted in only 2-3% CSO reduction at each downstream basin; an increase of 20% resulted in an 8-10% reduction.

The subcatchment-influence and perviousness analyses both speak to the complexity of this system. Improvements are expected to result in local benefits, primarily at "upstream" locations, but as flows combine, benefits are obscured

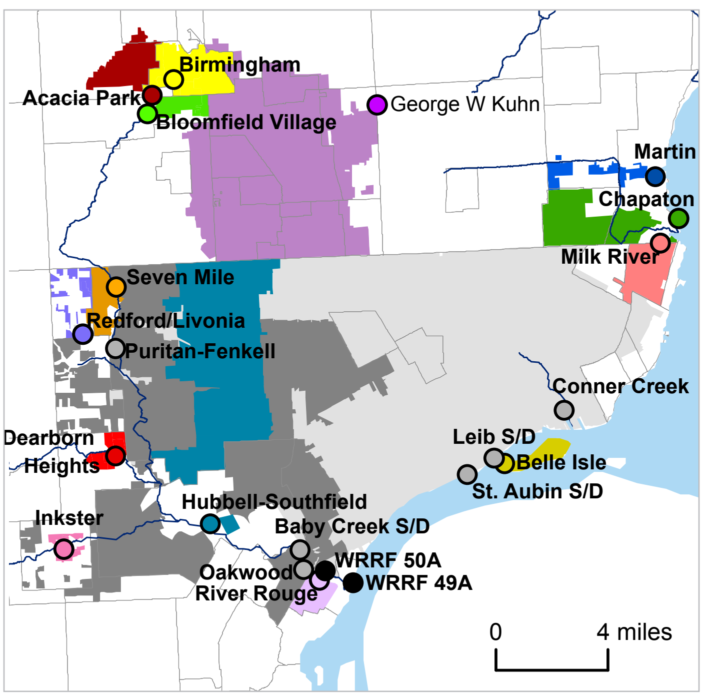

Figure 29. Approximate contribution areas for retention basins (RTBs) and screening and disinfection (S/D) facilities. Boundaries are not always strict, however, due to the complexity of the system's flows and operations. Gray lines are political boundaries. RTBs are represented by circles colored to correspond to the color of their contribution area. Dark gray areas are not controlled by an RTB. No spatial data delineating the contribution areas were available for RTBs shaded gray, or for the light gray area on the map, in part due to the increasing complexity of the system in these lower portions.

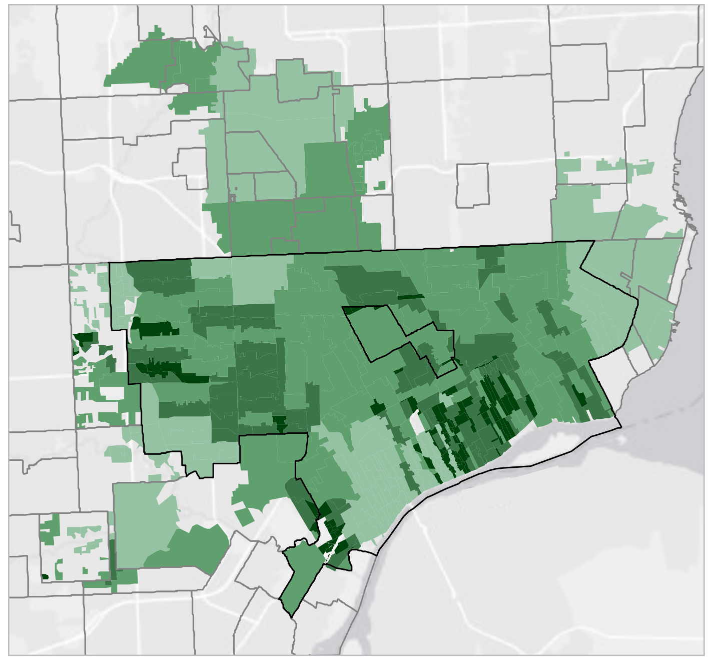

Figure 30. Results of "disconnection" analysis weighted by subcatchment impervious area. Gray lines are municipal boundaries, and black outline is city limit of Detroit. Data were divided into four quartiles, represented by the four shades of green. Darker subcatchments are ones that, if disconnected, could lead to a relatively larger reduction in wet weather discharge/CSOs under average/normal rainfall. Lighter colored subcatchments had less of an impact in reduction of CSOs per unit area. The map should be interpreted as a theoretical analysis of conversion of combined sewer to separated sewer. This should not be used as an indication of potential to place green infrastructure, as this is a more complex task. See analysis below.

and tapered in the lower reaches of the services area. Our analysis provides an assessment of the potential impacts of improved land cover and soil conditions. While it does not provide a realistic implementation guide, it is a baseline assessment of which subcatchments are most influential to CSOs.

Green infrastructure (GI) - We assessed two types of commonly implemented green infrastructure (GI): bioretention cells and permeable pavement, each equipped with underdrains to comply with local soil conditions. We implemented each separately over the area of the combined sewer region. We increased coverage of each GI incrementally from 0% to 20% to generate response curves showing percent change in CSO volume at each of the 14 modeled CSO outfalls separately, as well as percent change in CSO volume for the entire system (Figure 31). As with the exercise on pervious land cover, these response curves are

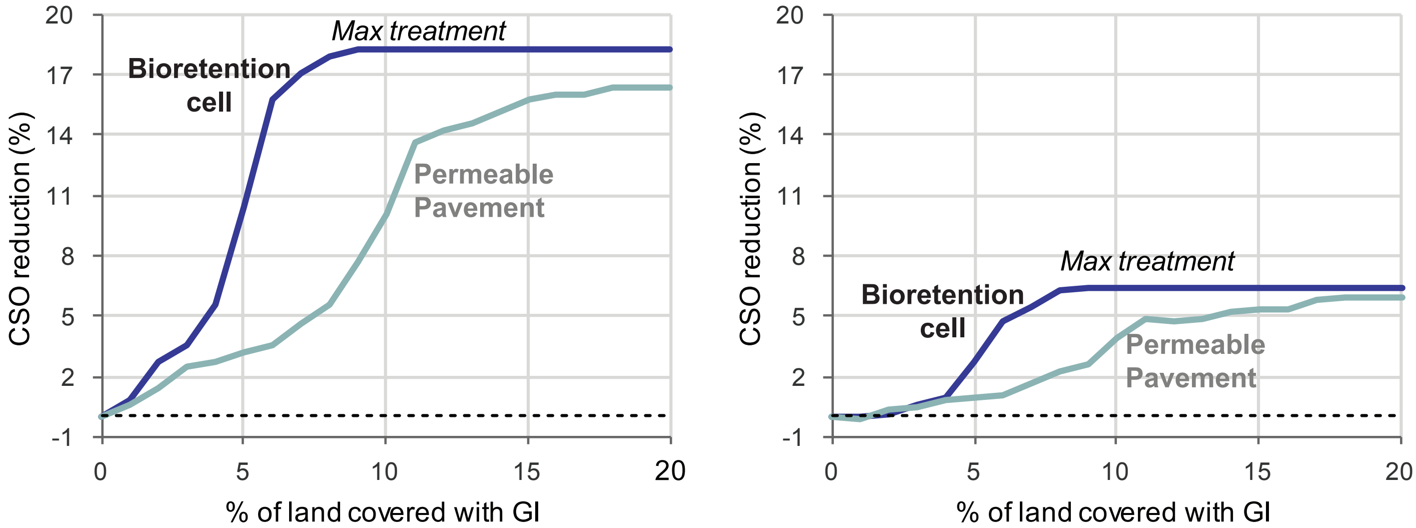

Figure 31. Reduction in CSO volume across all 14 outfalls under normal (left) and extreme (right) rainfall scenarios. Percent reductions are based on baselines of 1,038 million gallons for the normal rainfall scenario and 2,712 million gallons for the extreme rain scenario. Dashed line represents 0 reduction; note very small negative reductions (i.e., increases in CSO) under extreme rainfall conditions at low percent implementations of both GI types.

not intended to provide realistic implementation goals, but rather an understanding about the range of potential impacts GI may produce. Full details of the model parameters used for the GI scenarios are provided in the report supplemental information.

The results followed the same general pattern we found when we increased pervious area. For "upstream" CSO outfalls and for the system overall (Figure 30), GI could generally reduce overflow volumes under normal rainfall, but had limited effects under extreme storms. "Downstream" CSO outfalls were not substantially affected by GI under either rainfall scenario. Bioretention cells generally performed better than permeable pavement at reducing CSOs. At some RTBs, however, under the extreme rainfall scenario, CSOs increased in volume as the amount of GI implemented increased up to 8%. This is because bioretention cells hold back water and release it gradually through an underdrain, which shifts the peak of the flow without significantly affecting its magnitude. Large storms can take days to drain through the system, and so some GI may not reduce CSOs, but simply change when they occur. As such, placement of GI must be placed and designed with the broader system in mind, as outcomes may be marginal or even negative. This speaks to the complexity of the system and the need to incorporate systems-thinking when placing GI.

OPTIONS FOR THE GLWA SEWER SERVICE AREA

A balanced portfolio of interventions may help reduce phosphorus loads from the metro Detroit area. These include improved treatment at the WRRF, infrastructure improvements, and the potential for real-time control.

Reducing urban phosphorus loads through improved recovery of nutrients in wastewater - Phosphorus loads in effluent discharged from the GLWA WRRF are affected by several variables, including the amount of phosphorus that flows into the facility and treatment efficiency. While the city of Detroit has experienced population fluctuations, the overall population across the facility's service area has remained consistent. As such, the significant load reduction of phosphorus from the facility seen over the past decade resulted from an improvement of treatment operations. The facility contributes 13% of the Detroit River's total phosphorus load to Lake Erie, so any improvements to the treatment process stands to provide a centralized, manageable, and high-impact means to reduce loads. While beyond the scope of our study, treatment processes and technologies are continually evolving, and there may be potential for improved treatment at the facility in the future. While non-trivial in technological, human resource and financial costs, improving treatment operations could potentially have one of the biggest impacts on reducing metro Detroit's urban phosphorus load.

Infrastructure improvements: green and gray - Given the complexity of the collection system, no single solution for reducing CSOs is apparent. GI shows promise for reducing local CSOs at upstream catchments and could play a significant role when focused in these regions. The benefits of these upstream reductions may become muted downstream, however, and thus may not play a large role in reducing overall CSOs across the system. More classic gray infrastructure solutions, such as extra storage, could help alleviate the downstream burden; these two options could complement each other. We also note that our GI analysis focused solely on CSO reduction and that there are many additional reasons for implementing GI. Other benefits, such as enhanced community well-being, impact on non-phosphorus water quality issues, real-estate and urban habitat enhancement, are all highly relevant components of urban planning. While beyond the scope of our study, these and other benefits should be weighed as part of a broader GI implementation.

Real-time control - Collection systems have many infrastructure assets that can potentially be turned on and off in real time. These include pumps, gates, and valves that could be operated during storm events to dynamically provide storage opportunities. This could allow the current system to be used more efficiently. This was not evaluated in our study, but recent simulations show potential in applying autonomous solutions. More information on these technologies can be found on open-storm.org, an open source portal for the real-time control of stormwater systems. A specific report, analyzing the potential of real-time control on the GLWA system will be published on this web portal in the coming year.

STRATEGIES FOR SUBURBAN AREAS

SWAT allowed us to explore GI scenarios implemented in urban/suburban areas beyond the GLWA sewer service area modeled by SWMM. We tested two scenarios for the highly urbanized Rouge and Clinton watersheds: (1) reducing impervious surface area by changing the land cover to pervious but bare surfaces that increase infiltration, similar to practices such as pervious pavement, and (2) reducing impervious area by changing the land cover to vegetated area, increasing both infiltration and evapotranspiration, which is similar to practices such as planting rain gardens, vegetated swales, or trees. This latter scenario was much more effective at reducing TP and DRP because vegetation increases evapotranspiration which reduces stormwater flow (Figure 32). The Rouge watershed responds more than the Clinton to these scenarios because a higher proportion of the Rouge area is impervious. However, because the nonpoint source TP load from the Clinton is about three times that of Rouge, the absolute loads reduced from these watersheds are roughly equivalent for the same percent increase in perviousness. These analyses are not meant to represent real world conditions, but rather provide an indication of load reductions possible through GI.

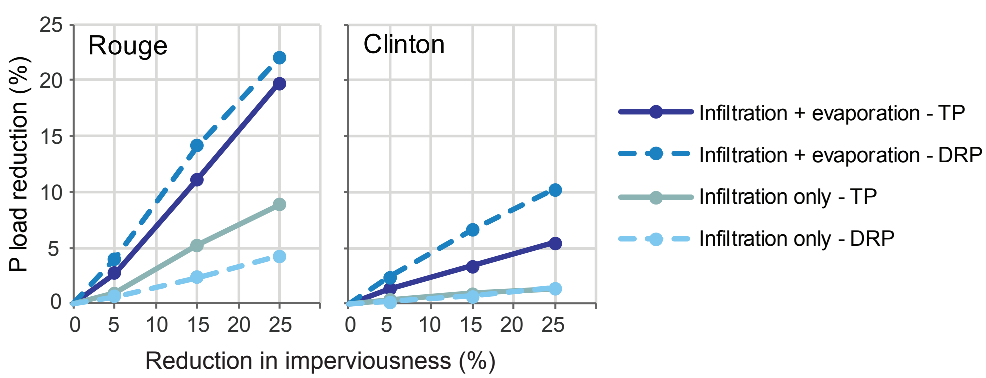

Figure 32. TP and DRP response curves for the Rouge and Clinton River watersheds for vegetated and unvegetated permeable areas.

GREEN INFRASTRUCTURE EXAMPLES

Phosphorus is fairly concentrated in human waste and is one of the pollutants wastewater treatment systems are designed to remove. Although the majority of phosphorus contributions from urban areas come from point sources, stormwater runoff can trigger combined sewer overflows as well as wet weather discharges from wastewater treatment plants. Runoff from suburban and urban areas typically has very low levels of phosphorus, but some turf and lawn fertilizers, feces from pets and wildlife, and leaf litter can make small contributions. This project evaluated three green infrastructure practices using two models.

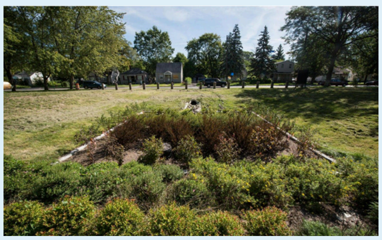

Photo: Dave Brenner

Bioretention cells are landscaped depressions that capture and filter stormwater runoff. They are often installed in lawns, along the edges of roads, or in the medians of parking lots, and typically have a mixture of sand and soil to promote infiltration as well as a drain to handle excess water. Rain gardens and bioswales are common types of bioretention cells. This practice was modeled using SWMM. We assumed a bioretention cell received water from an adjacent impervious area ten times its size, which means that maximum treatment is achieved when this practice covers 10% of a subcatchment. Our model also assumed each cell had an under drain, which improves drainage by diverting some water into the storm drain system, a common design feature in areas such as Detroit with dense clay soils. As a result, this practice served to delay but not remove flows to the stormwater system.

Photo credit: Achim Hering

Permeable pavement refers to the practice of replacing traditional pavement with alternative materials that allow rainwater to infiltrate through the surface and into the soil below. Materials available for this, such as interlocking pavers and specially formulated asphalt and concrete, are generally more expensive than traditional pavement. We simulated the impact of this practice using both SWMM and SWAT. SWMM assumed an area with permeable pavement received water from an adjacent impervious area five times its size and the installation included an underdrain, similar to the model simulation for bioretention cells. In SWAT, we converted different fractions of impervious area to unvegetated pervious areas, and assumed these areas only received direct rainfall and infiltration rates depended on the soil type and precipitation amount.

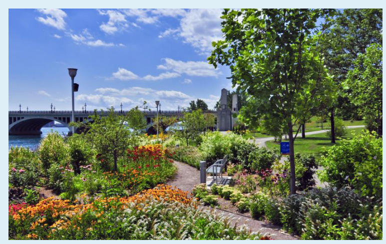

Photo: Detroit Riverfront Conservancy

Converting pavement into vegetation. We simulated the impact of converting impervious areas to permeable, vegetated areas using SWAT. This scenario simulates what could occur if a parking lot were converted to a park, for example. Unlike rain gardens, we assumed there was no additional drainage to these vegetated areas. SWAT simulated both infiltration into the soil and evapotranspiration by the plants in these areas, which together reduce runoff volumes.

SUMMARY

Because the load from the GLWA WRRF is the largest urban TP source and because the dry-weather contribution from the WRRF represent a major phosphorus contribution, improvements in treatment technologies stand to make a difference in phosphorus loads to Lake Erie. That said, such improvements may be expensive and a number of improvements have already been made over the past decade. While CSOs are not a major phosphorus source relative to the WRRF, the reduction of CSOs could still make broader positive environmental impacts beyond reducing phosphorus loads. To that end, green infrastructure shows a relatively larger impact on reducing upstream CSOs, while downstream overflows are guided by other system complexities. Overall, green infrastructure placement should consider timing of flows, since it may shift the peak of the hydrograph, which could be desirable or not depending on local conditions. While beyond the scope of this study, “gray” solutions and emerging “smart” control solution could also be considered to reduce downstream overflows. SWAT results indicate that creating more vegetated and pervious surfaces, rather than just pervious surfaces alone, is more effective for reducing runoff volume and phosphorus loads.

7 OPTIONS FOR MEETING PHOSPHORUS LOADING TARGETS

WHERE ARE WE NOW, AND WHERE DO WE HAVE TO GO?

In February 2016, the US and Canada revised phosphorus loading targets for Lake Erie under the *Great Lakes Water Quality Agreement*. One of the new targets calls for a 40% reduction in annual total phosphorus (TP) inputs to the western and central basins relative to 2008 levels. Another target relevant to this study is a 40% reduction of spring TP and dissolved reactive phosphorus (DRP) from the Thames River watershed. We explored what management actions can help meet a 40% annual TP goal for the Detroit River and a 40% spring TP and DRP goal for the Thames.

Our Detroit River loading estimates for 2008 are somewhat higher than those that were available when the targets were set (Maccoux et al. 2016), as described above, primarily because of updates in methods and loading estimates. As such, the calculations to follow may represent different absolute values for reduction; however, the relative contributions are unlikely to be very different. As the US and Canada adaptively manage their Domestic Action Plans, which were established to determine state, provincial, and federal actions related to these goals, this material may help them reevaluate the load reductions from the St. Clair-Detroit River watershed. Our new understanding of the contribution from Lake Huron suggests they may need to adjust reduction allocations from the St. Clair-Detroit River System watershed.

THE ROLE OF THE LAKE HURON LOAD

While the geographic extent of our data and models limited the options we explored to those within the project watershed, this assessment can help identify what remaining load, if any, would need to be reduced from Lake Huron sources.

The fact that 54% of the TP load to Lake Erie from the Detroit River originates in Lake Huron, even though 20% of the total load to Lake St. Clair is retained in that lake, is a reminder that all water resources in the Great Lakes are part of a single system, and that upstream nutrient sources are critically important to consider. We have reported that the current contribution to the Detroit River load from Lake Huron could be as much as twice the load currently estimated from measurements, and that the previously unmeasured contribution has been increasing due to climate change. The previously unmeasured contribution to the Detroit River load appears to come from sediment resuspended along Lake Huron's southeast region, and any attempts to improve that estimate or to reduce that load will require additional analyses of its sources, phosphorus content, event frequency, and movement toward the outflow to the St. Clair River. It should be possible to enhance monitoring, thereby improving load estimates, by including continuous measurement of phosphorus surrogates, such as turbidity, that can be correlated with phosphorus concentrations (e.g., Robertson et al. 2018).

HOW COULD WE GET TO THE ANNUAL TP TARGET USING WATERSHED SOURCES?

As outlined in Chapter 2, the decline in the load to Lake Erie between 1998 and 2008 was due primarily to a reduction in the Lake Huron load driven by ecological changes in that lake. The decline in the total load between 2008 and the current average (2013-2016) was due primarily to reduced phosphorus discharge from the Great Lakes Water Authority's Water Resource Recovery Facility (Figure 33), and the increase in the Lake Huron load since 2008 was driven by increases in the previously unaccounted for sediment load.

Our estimate of the 2008 Detroit River load was 3,096 MTA. A 40% reduction would result in a target load of 1,858 MTA.

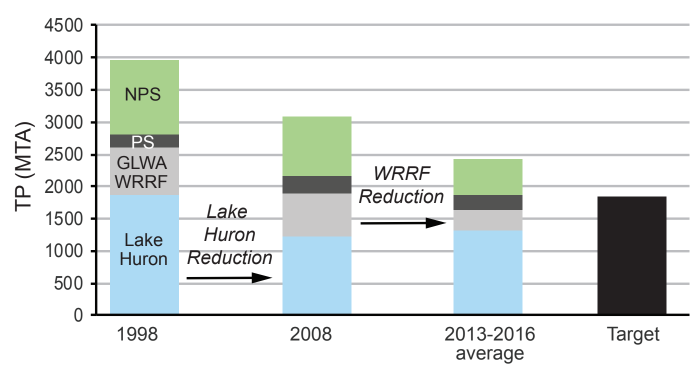

Figure 33. Contributions to the Detroit River TP load to Lake Erie for the water years 1998, 2008, and the 4-year average 2013- 2016. The target represents a 40% reduction from the 2008 load.

Because the 2013-2016 average Detroit River loads had already declined to 2,425 MTA, the remaining amount to reduce is 567 MTA (Figure 33). If the US and Canada seek to reduce the remaining 567 MTA from the St. Clair-Detroit River watershed load, they will need to reduce those sources by 51% of the current load (2013-2016 average). This is because of the current 2,425 MTA load, 1,110 MTA (46%) comes from the watershed, and the rest (54%) is from Lake Huron.

Of the load originating from within the watershed, nonpoint sources contribute more than point sources (798 and 602 MTA, respectively). Average annual TP contributions from the US (798 MTA) are more than those from Canada (601 MTA). Point sources account for 63% of the US TP loads, but only 19% of the Canadian TP loads. Therefore, one might expect different areas of focus for the two countries.

Agricultural sources – Bundling agricultural management practices worked better than implementing single practices for reducing both TP and DRP loads from the agriculturally dominated watersheds of the Thames, Sydenham, and Black rivers (Figure 23).

Among the agricultural management strategies tested, reducing the rate of fertilizer application did not appear to be particularly necessary as long as cover crops and subsurface fertilizer placement are employed. However, combining three of the following practices: cover crops, filter strips, wetlands, and subsurface placement of fertilizer, resulted in TP reductions from the sub-watersheds greater than 50% and suggest that a flexible approach, where practices can be combined to match the needs and preferences of producers, will be most successful.

Our results also suggested that focusing the practices on 55% of the land with the highest TP and DRP loss rates achieve reductions on the order of the *Great Lakes Water Quality Agreement* targets. While promising, this level of focus is also difficult to accomplish. Programs encouraging adoption of agricultural BMPs are typically voluntary in nature, therefore often having a "scatter-gun" effect. Movement toward more focusing can be helped by assigning staff, program eligibility, and funding to specific watershed or regions that have higher phosphorus loss rates, but more data is needed to help farmers make effective decisions at the field scale to determine their own best practices. Unfortunately, the tools needed to support focusing are hampered by limited access to the necessary high-resolution data, such as what practices already exist on specific parts of the landscape, due to lack of funding, interest, or capacity by government agencies, and uncertainty by farmers about the use of those data.

Because point sources contribute roughly 19% of the Canadian TP, it makes most sense to emphasize control of nonpoint, primarily agricultural, sources in the Canadian portion of the watershed provided the unit cost of phosphorus reduction from agricultural nonpoint sources are found to be lower than reducing urban sources.

Reaching spring TP and DRP targets for the Thames River - To ensure healthy nearshore ecosystems, the Ontario-Canada action plan called for a 40% reduction in spring TP and DRP loads from several watersheds, including the Thames River watershed, the only one within our study region. In testing several of the bundled scenarios designed to address the annual TP reduction for the Detroit River, we found that the ones we tested for the spring TP and DRP loads for the Thames, Sydenham, and Black rivers produced even larger percentage reductions than for the annual load. This model result is encouraging because it suggests that spring TP and DRP loads are more responsive than annual loads.

Urban sources – Because point sources account for 66% of US watershed contributions of TP to the Detroit River's load to Lake Erie, it is logical to focus on approaches that reduce input from these sources. An obvious target could be the GLWA Water Resources Recovery Facility (WRRF) because it contributes most of the urban phosphorus load in the St. Clair-Detroit River watershed. However, since 2010 substantial load reductions from this facility have already been made, and the high costs of further technological enhancement make more improvements difficult. Research on nutrient capture continues to evolve, however, and technological solutions may come down in cost to make it suitable for implementation at Detroit's WRRF.

Because combined sewer overflows (CSOs) are a small part of the overall urban TP load, efforts to reduce their load would contribute very little to the annual TP contribution to the Detroit River. However, CSOs present many other public health issues and local water quality concerns. Therefore a focus on reducing treated and untreated CSO discharges is a critical component of planning for green and gray infrastructure. It is important to note that that the high cost of controlling additional urban sources, particularly CSOs, increases the burden on ratepayers.

Given the complexity of the collection system, no single solution seems to exist for remedying CSOs. Green infrastructure shows promise for reducing discharges from individual CSO basins located further away and upstream from the WRRF, and could play a role when focused in these regions. There seems to be less potential for green infrastructure to control wet weather discharges from basins closer to the facility, and thus green infrastructure may not be able to contribute significantly to reducing overall CSOs across the whole system. More gray infrastructure solutions, such as extra storage, could also help alleviate overflows. The GLWA sewer system has many assets that can be turned on and off in real time, allowing the current system to control flows more efficiently. Such solutions could enhance any future construction projects, too, by optimizing the operation of the system on a storm-by-storm basis. Such technologies are new, however, and must be vetted before being considered as a complement to green and gray efforts.

CLIMATE CHANGE WILL LIKELY MAKE REACHING TARGETS MORE DIFFICULT

There are two common ways of assessing future climate change impacts on watershed outputs: 1) using climate data from downscaled regional or global climate models, or 2) using a delta change approach that assumes average changes relative to their current values. Because we did not have downscaled climate model data for our watersheds, we used the delta change approach based on six downscaled climate model results for the Maumee River Watershed. We used monthly averaged, worst case precipitation and temperature changes between mid-century (2046-2065) and the present (1996-2015). All but one climate model projected increases in annual precipitation, and all models projected an increase in temperature between 2.5oC and 3oC. The 6-model annual average changes in precipitation and temperature were +6.2% and +2.7oC, respectively.

Similar to most analyses for this region (Daloğlu et al. 2012, Bosch et al. 2014, Verma et al. 2015, Jarvie et al. 2017) and most of the US (Sinha et al. 2017), we found that increases in the timing and intensity of spring precipitation will lead to increased runoff and phosphorus loads. Also similar to recent analysis for the Maumee watershed, (Kalcic et al. 2019), our simulations indicate that increased temperature appears to mitigate some of the spring runoff because less snowpack reduces the intensity of spring runoff and increased evapotranspiration means there is less water available to runoff. We found that, on average across the watershed, higher precipitation alone increased TP loads by 25% and DRP loads by 20%. While somewhat mitigating the impact, combining higher precipitation and temperature still increased TP loads by 9.3% and DRP loads by 7.2%. Therefore, while increases in temperature appear to mitigate some of the precipitation impact, projected future climates are still likely to make load reductions more difficult. Under these conditions, a stronger focus on practices that prevent the runoff or that hold water back will likely be more successful. Our analyses suggest a focus on subsurface fertilizer placement (to prevent runoff) and wetlands (to hold back water), however other practices beyond those tested here may be needed to mitigate the more extreme precipitation events that can overwhelm practices put in place.

If storms become more frequent and intense, additional pressure will be placed on the Detroit stormwater system, and the collection system must be made more robust to CSOs. As we demonstrated, the system is a complex interconnection of pipes, channels, and land-cover that cannot be expected to respond linearly by changes in climate. In fact, benefits could become marginal if the altered practices are not carried out in a system context. If storms get larger, we would anticipate that CSOs would increase proportionally more. More analysis is required to evaluate these and other impacts of climate change.

It is also important to recognize that climate also influences dynamics within Lake St. Clair and Lake Erie. Increasing temperatures and longer periods of lake stratification can lead to an earlier and longer algae growing season, as well as increased organic matter that promotes more hypoxic waters. For example, Rucinski et al. (2016) showed that variation in meteorology (via lake thermal stratification) explained almost nine times as much interannual variability in the size of hypoxic area compared to variation in phosphorus loading, and that deeper stratification caused by warmer, longer summers led to larger hypoxic areas. To advance scientific progress and better inform management, the interactions between climate and land management, as well as climate impacts within the lake, must be better evaluated in order to assess future changes in both the watershed and Lake Erie.

DOMESTIC ACTION PLANS

The US Domestic Action Plan focuses on supporting states with financial and technical assistance as they develop nutrient reduction strategies tailored to their unique set of challenges and opportunities. This effort focuses on: 1) accelerating nutrient reductions, 2) enhancing monitoring and research efforts to better understand the effectiveness of actions taken to reduce nutrient loadings, and 3) identifying ways to improve implementation of federal programs and policies. The actions focus largely on agricultural source reductions, and runoff and drainage management, with some additional focus on urban green infrastructure projects. US federal support and cooperation with the State of Michigan is most relevant to the Detroit River load.

While the **Michigan Domestic Action Plan** has several additional commitments for the western basin of Lake Erie, the ones most relevant to the Detroit River include: maintaining the reductions achieved in the Great Lakes Water Authority Wastewater Resource Recovery Facility; achieving reductions in phosphorus discharged from the Wayne County Downriver Wastewater Treatment Facility; identifying the suite of best management practices that work collectively to reduce both TP and DRP; increasing and maintaining Michigan Agriculture Environmental Assurance Program practice implementation and verification for long-term water quality improvement; and promoting wetland restoration and other land management initiatives to reduce phosphorus loading.

The **Canada-Ontario Domestic Action Plan** outlines a range of Federal and Provincial efforts to maintain and enhance programs, policies, and commitments that support watershed-based and nearshore strategies, and community-based planning to reduce phosphorus loading from agricultural, rural, and urban areas, including improvements in sewage treatment and stormwater systems, supporting improved fertilizer management, and emphasizing the use of conservation programs on crop lands.

Adaptive management - Each of the Domestic Action Plans emphasize that targets and approaches to achieving them are not static. For systems this complex and dynamic, it is critical to set targets, take action, monitor the results, and make adjustments as necessary – Adaptive Management. In a watershed as large and complex as this one, it is critical that effective monitoring at the right scale be in place to track progress resulting from management actions, and adjust as appropriate.

Much of the analysis and assessment we provide here is new since the 2016 phosphorus loading targets were set and the action plans developed, especially for the St. Clair and Detroit River System watershed. Therefore, we anticipate our results will be helpful as the plans evolve:

- Lake Huron is a more significant source of upstream TP than was previously realized, and it may require larger reductions from the watershed and/or attention to the Lake Huron sources in order to reach current targets;
- While single agricultural management practices can be effective in reducing TP and DRP loads, they do not appear to reach the 40% target reductions; bundles of practices achieve higher and more consistent reductions. Adopting the most effective bundles in a smaller fraction of the highest source areas is just as effective as attempting to implement them everywhere, and likely at a much lower cost. The diversity of effective bundles provides flexibility for focused implementation across this complex watershed.
- Scenarios that achieve or surpass the 40% reduction of annual loads appear to be even more effective for reducing spring loads from the Thames, Sydenham, and Black rivers.
- While CSOs and urban runoff are not large contributors to the Detroit River phosphorus load, efforts to reduce flow into the storm system through gray and green infrastructure and increasing perviousness with vegetative cover have local benefits. It may be most beneficial to focus on the upper reaches of the sewer system where green infrastructure can be connected to reductions in specific CSOs.
- Climate change is likely to lead to stronger spring precipitation events, and efforts to reduce water flow, as well as reducing the phosphorus concentration in that water, are likely to be needed.

To understand and assess the relative sources of, contributions to, and actions to reduce loads to Lake Erie from the Detroit River required assembling diverse data sets from both the US and Canada; developing, calibrating, and validating diverse models at different scales of time and space; and using both data and models to explore potential management options. This effort, coupled with similar ones developed for the Huron River (e.g., Xu et al. 2017), the River Raisin (e.g., Muenich et al. 2017), and the Maumee River (Scavia et al. 2017), provide tools that can be used to guide policies and practices as the countries work within the *Great Lakes Water Quality Agreement* adaptive management framework. The process enables both adjustments in action plans and improvements of models and other assessment tools as new information becomes available.

FOR MORE INFORMATION:

Report supplemental information as well as additional products from this project are available here: myumi.ch/detroit-river

The project web page will be updated periodically to include:

- Journal articles developed by the team
- Documentation of data sources and methods for SWAT, SWMM and the urban sources assessment.
- Factsheets, slides, and graphics

To request PDF copies of team journal articles, email Don Scavia at: scavia@umich.edu

ACKNOWLEDGEMENTS

We gratefully acknowledge our project sponsor the Fred A. and Barbara M. Erb Family Foundation. In addition, to providing a grant (grant# 903) that supported most of the research summarized in this report, Foundation staff, especially Melissa Damaschke, provided important guidance and insights as we were planning and executing the project.

We sincerely appreciate the many contributions of our project advisory group, which generously shared their expertise and took time to review documents and attend meetings. The group helped us access additional data, improve model assumptions, and stay connected to an evolving policy context. The Appendix lists all the advisory group members. The report supplemental information outlines the group meetings and conference calls and summarizes a few of the ways the team responded to the priorities and suggestions of the advisory group.

In addition to the advisory group, this project benefited from consultations with experts that provided insights, advice and in many cases data. We would like the thank the following individuals: Dave Schwab and Rob Goodspeed from the University of Michigan; Margaret Kalcic from Ohio State University; Robert Hirsch from USGS; Debbie Burniston, Sean Backus, Luis Leon, and Reza Valipour from Environment and Climate Change Canada; Mary Lynn Semegen, Bill Creal, and Catherine Willey from the Great Lakes Water Authority; Pamela Joose from Agriculture and Agri-Food Canada; Karen Maaskant from Upper Thames River Conservation Authority; Matthew Maccoux from the Milwaukee Metropolitan Sewerage District; Dong Zhang from the Ontario Ministry of Environment and Climate Change; Edward Lynch from Detroit Future Cities; and Rick Duff from the Natural Resources Conservation Service.

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APPENDIX. ADVISORY GROUP

We recruited a large advisory group for this project to maximize input from diverse sectors, geographies and areas of expertise. The group had multiple opportunities to review and comment on project results but the content of the final report is solely the responsibility of the project team. Report supplemental information outlines project meetings and key outcomes from the project.

REPRESENTATIVE	ORGANIZATION
Larry Antosch	Ohio Farm Bureau
Phil Argiroff	Michigan Dept. of Environmental Quality
Raj Bejankiwar	International Joint Commission
Mary Bohling	Detroit River Area of Concern Public Advisory Council
Tim Boring	Michigan Agri-Business Association
Tom Bruulsema Heidi Peterson	International Plant Nutrition Institute
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