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Urban total phosphorus loads to the St. Clair-Detroit River System

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ABSTRACT

The St. Clair-Detroit River System watershed is a large, binational watershed draining into the connecting channel between lakes Huron and Erie. In addition to extensive agricultural lands, it contains large urban areas that discharge phosphorus from point source facilities, runoff of impervious surfaces, and overflows of combined sewers. To help guide actions to reduce phosphorus input to Lake Erie, we analyzed the spatial and temporal dynamics of loads from the three largest urban areas in the watershed (southeast Michigan; Windsor, Ontario; and London, Ontario), and used a previously calibrated storm water management model (SWMM) to explore options for reducing loads around metro Detroit. Point sources in these three urban areas contribute, on average, 81% of the total urban load and 19% of the Detroit River's total phosphorus (TP) load to Lake Erie, while combined sewer overflows and runoff both contribute about 10% each to the urban load and about 2.5% each to the Detroit River's load to Lake Erie. Most of the urban load (56%) comes from a single point source, the wastewater treatment facility in Detroit; however, TP loads from that facility have decreased by about 51% since 2008 due to improvements in wastewater treatment. Model simulations suggest that increasing pervious land area or implementing green infrastructure could help reduce combined sewer overflows in certain upper portions of the metro Detroit sewer system, but reductions were much less expressed for wet-weather discharge from the system.

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Introduction

The return in the 1990s of harmful algal blooms and oxygen depletion (hypoxia) in Lake Erie (Scavia et al., 2014) included one of its largest recorded harmful algal blooms (e.g., Michalak et al., 2013), a "do not drink" advisory for the public water supply for over 400,000 people in Toledo, Ohio, and increased hypoxia that can impact fish and fisheries (Brandt et al., 2011; Scavia et al., 2014; Ludsins et al., 2001) at sizes not seen since the 1970s. Because phosphorus (P) is the primary driver of Lake Erie algal blooms and hypoxia (Bertani et al., 2016; Rucinski et al., 2016; Obenour et al., 2014; Scavia et al., 2014), the United States and Canada set new targets to reduce annual and spring total P (TP) and dissolved reactive P (DRP) loads (GLWQA, 2012). Substantial efforts in both countries are being designed to reach those targets, and it is critical to have a thorough understanding of the sources and dynamics of the loads, especially because the countries are committed to adaptive management strategies.

As those action plans are reviewed and revised, substantial attention will continue to be placed on loads from the Detroit and Maumee rivers because they have been reported to contribute respectively 41% and 48% 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). Several studies have focused on P loads from the heavily agricultural Maumee watershed (Scavia et al., 2017; Kalcic et al., 2016; Muenich et al., 2016), and more recently from the Detroit River watershed (Scavia et al., 2019a; Hu et al., 2018; Bocaniov and Scavia, 2018; Dagnew et al., 2019a,b) as part of an integrated assessment of its phosphorus sources and loads (Scavia et al., 2019b). This study is part of that assessment.

The Detroit River is the main conduit to Lake Erie for flow and nutrients from Lake Huron and from the 19,040 km² St. Clair-Detroit River watershed (Fig. 1) that contains both large urban areas and extensive agriculture. While most (58%) of its TP load comes from Lake Huron, the rest is divided between watershed point sources (18%) and non-point sources (24%) (Scavia et al., 2019b). Dagnew et al. (2019a,b) evaluated potential watershed-wide strategies for reducing non-point source loads. The details of urban P sources and dynamics are often neglected in large

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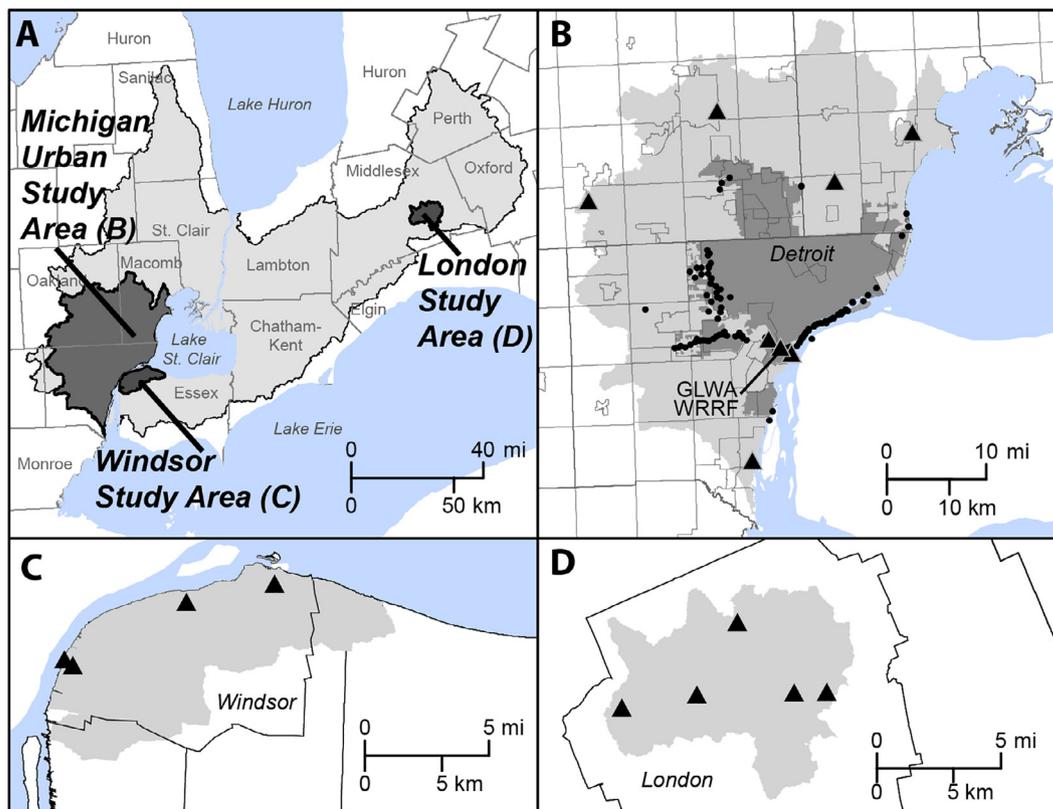


Fig. 1. (A) Location of three largest urban areas (dark gray) within the St. Clair-Detroit River watershed (light gray); (B) Michigan urban study area (light gray) and the region's combined sewer system area (dark gray). (C) Windsor study area and (D) London study area. Triangles indicate point source facilities and circles are CSO outfalls. Gray lines are municipal boundaries.

watersheds dominated by agricultural inputs (Kalmykova et al., 2012), despite a finding by Hobbie et al. (2017) that only 22% of net P inputs (i.e., total P inputs minus the biomass removal) to urban areas are retained, with the rest flushed to waste- and storm-water drains and ultimately discharged to water bodies.

In the urban environment, the spatial and temporal dynamics of urban TP loads are subject to many factors, including rainfall intensity, operation of control units, and wastewater treatment level. It can thus be useful to attribute the loads to runoff, combined sewer system overflows, and point source discharges as a way to understand urban TP loads. Herein, we focus on TP loads from the three primary urban sources, runoff, combined sewer overflows (CSOs), and point sources, from the three major urban areas: southeast Michigan; Windsor, Ontario; and London, Ontario (Fig. 1). Quantifying these loads can help determine where reductions should be prioritized, while paving the way to design of strategies to reduce them.

Reduction of urban TP loads from point sources is often dealt with by improvement of wastewater treatment technologies, including, for example, the tertiary treatment in some cases (National Research Council, 2000), while TP from CSOs and runoff can be reduced through gray infrastructure (e.g., CSO retention treatment basins) and green infrastructure (e.g., bioretention cells and permeable pavements) (Baek et al., 2015; Joksimovic and Alam, 2014). However, selections of these practices are complex, depending on a variety of factors, such as locations, costs of implementation and maintenance, and TP removal efficiency. Physically-based models (e.g., EPA Stormwater Management Model (SWMM), MIKE URBAN and HEC-HMS, to name a few) couple hydrology and hydraulics, numerically computing processes such as infiltration and shallow water flow. Once calibrated, they can be well suited

to evaluate different practices across fine spatiotemporal resolutions (Baek et al., 2015).

In this study, our objectives were to quantify current TP loads from different sources in the St. Clair-Detroit River System's three major urban areas: southeast Michigan; Windsor, Ontario; and London, Ontario, and explore load reduction scenarios using a calibrated EPA Stormwater Management Model (SWMM) for the metro Detroit area.

Methods

Study areas

To delineate major urban areas, we selected subbasins (HUC-12) with more than 80% urban land cover in Michigan (National Land Cover Database, 2011), and more than 60% in Ontario (Agriculture and Agri-food Canada, 2011). This resulted in study areas around southeast Michigan; Windsor, Ontario; and London, Ontario, and more accurately captured the urban areas than using political boundaries (Fig. 1). The lower threshold was necessary in Ontario because the urban areas there are less dense than in southeast Michigan and were not well captured with an 80% threshold. The Michigan urban study area (Fig. 1b) covered 2390 km² and contained over 3.1 million people, while Windsor (Fig. 1c) and London (Fig. 1d) study areas were 149 km² and 138 km², respectively, with populations of about 211,000 and 366,000 (SI: Population Analysis).

We estimated TP loads from point sources, combined sewer overflows (CSOs), and runoff for these three areas. TP concentrations and discharge volumes from point sources and CSO outfalls were obtained from several data repositories (Electronic Supplementary Material (ESM) Table S1), and runoff was calculated as

described below. Results are presented as averages for water years 2013–2016, though we used longer datasets to examine trends and for interpolation of missing data.

Point sources

There are ten point source facilities in the Michigan urban study area (Fig. 1b, ESM Table S2) that are permitted to release phosphorus to surface water and that had discharge events during our study period. These include wastewater treatment plants and other industrial facilities that have outfalls with regular discharge, independent of water conditions - as compared to CSOs, which are wet weather discharges. Of these, the Great Lakes Water Authority Water Resource Recovery Facility (GLWA WRRF) in Detroit is by far the largest. It is one of the largest wastewater treatment facilities in the world serving over three million people in Detroit and the surrounding 76 communities and treating an average 650 million gallons (2460 million liters) of wastewater per day (DWSD, 2013). We used daily TP concentration and discharge data provided by GLWA to calculate TP loads from the facility's regular, dry weather outfall and its two wet-weather outfalls, which are used when the facility reaches its treatment capacity. The discharge from the dry-weather outfall receives full primary and secondary treatment, while the wet-weather discharge is only partially treated. We considered the sum of the load from these three outfalls as the point source discharge for the facility.

For the other nine point sources in the Michigan urban study area, as well as for the five in London and the four in Windsor, TP loads were calculated from monthly discharge volumes and monthly average TP concentration. When no data were available for a given month, the average monthly load for the same month in other years was used. If no data were available for the same month in other years, the overall average monthly load for the outfall was used. Michigan data were obtained from the EPA Enforcement and Compliance History Online (ECHO) database, and Windsor and London data were obtained from the Ontario Ministry of the Environment and Climate Change (MOECC).

Combined sewer overflows

The Michigan urban study area contains 26 treated and 78 untreated CSO outfalls (ESM Table S3) that had at least one overflow during the study period. There are more CSO outfalls in the region than these, but they did not have overflows between 2013 and 2016. Treated CSOs are most often discharges from the retention treatment basins (RTBs) which hold back water during wet weather and then release it to the treatment facility when the facility regains capacity. If RTBs reach capacity, though, the water is discharged after receiving primary treatment (i.e., settling and chlorination). Treated CSOs also occur as discharges from screening and disinfection (S/D) facilities, which provide some water treatment but do not store water. Untreated CSOs can occur where RTBs or S/D facilities are not present and sewer water is discharged directly into local waterways without treatment.

For the seven treated outfalls operated by GLWA, we calculated TP loads from daily concentration and flow data provided by GLWA. For all other treated CSOs, event-based discharge volumes were obtained from the Michigan Department of Environmental Quality (MDEQ) online CSO/SSO database, and monthly TP concentrations were retrieved from the EPA ECHO database. If the concentration data were missing for an event, we used the median concentration from that outfall for the event. If the concentration data from a specific outfall were unavailable, we used the median from a different outfall at the same facility. For untreated CSO outfalls, event-based discharge volume was obtained from the MDEQ database, but no concentration measurements were available. We

assumed the TP concentration for all untreated CSOs was 1.25 mg/L, which is suggested by MDEQ. This is likely a conservative estimate because TP loads in untreated CSOs can vary based on factors such as duration of discharge and antecedent weather conditions, and the TP concentration in untreated CSOs is not expected to be as high as that of influent wastewater due to mixing with stormwater runoff.

Parts of the London and Windsor study areas also have combined sewer systems, but CSOs are only reported as wet-weather discharges at wastewater treatment plants, which occur when plant inflow exceeds treatment capacity. We considered these discharges as part of point sources, but distinguish them as “wet weather point source discharge” in the results where relevant. Discharge volumes were provided by the Ontario Ministry of the Environment and Climate Change (MOECC), but concentration measurements were not available. Because wet-weather flow usually receives primary treatment before it is discharged, we used the median TP concentration (0.67 mg/L) from discharges from the RTBs operated by GLWA for load calculations.

Runoff contributions

A regression model (Arnold et al., 2012; Tasker and Driver, 1988) based on impervious land cover and daily precipitation was used to calculate daily TP loads from runoff. Precipitation data were obtained from NOAA's Global Historical Climatology Network (GHCN) for the gauge station nearest to the centroid of each HUC-12 subbasin. If the daily value was missing at the nearest station, the nearest neighborhood method was used to interpolate the missing value. Total urban area and impervious land cover on the US side were calculated from the National Land Cover Database (2011), while at the Canadian areas were calculated based on Annual Crop Inventory Canada (ACIC; 2011–2015) and NOAA's Global Distribution and Density of Constructed Impervious Surfaces (GDDCIS) dataset (Elvidge et al., 2007). We used the regression model to calculate both upper and lower estimates for TP from runoff (see ESM Appendix S1 for Details of Runoff Calculation); here, we present the average.

Runoff was not calculated for the area with combined sewers in the Michigan study area because it is assumed that surface water from those areas enters the sewer system and either becomes part of CSO discharge or discharge from the WRRF. Spatial data locating the combined sewer areas in London and Windsor were not available, though, and therefore some unavoidable double counting occurred in calculating Canadian wet-weather discharge and runoff TP loads, but because loads were small it does not significantly impact final results.

Modeling load reduction scenarios

A physically-based hydrological and hydraulic model was developed in 1998 using the EPA Storm Water Management Model (SWMM) for the Detroit sewer collection system's 1,963.2 km² service area (Tenbroek et al., 1999) (Fig. 2). The model has 402 sub-catchments with unique land cover, soil, gray infrastructure, and connectivity to the sewer system. Using the latest version of the model released in 2012, Hu et al. (2018) developed a data-driven approach to calibrate the model against the volume discharge measurements at 12 retention basins, the two wet-weather outfalls at the WRRF, and for inflow to the WRRF (See SWMM Calibration Points in Fig. 2).

In this study, we used this improved version of the SWMM model to simulate the volume discharge of CSO over the combined sewer area in metro Detroit (Fig. 2). This is because no measurements of CSO TP concentration are available. Thus, the study uses CSO discharge as the proxy for the CSO TP loads by assuming con-

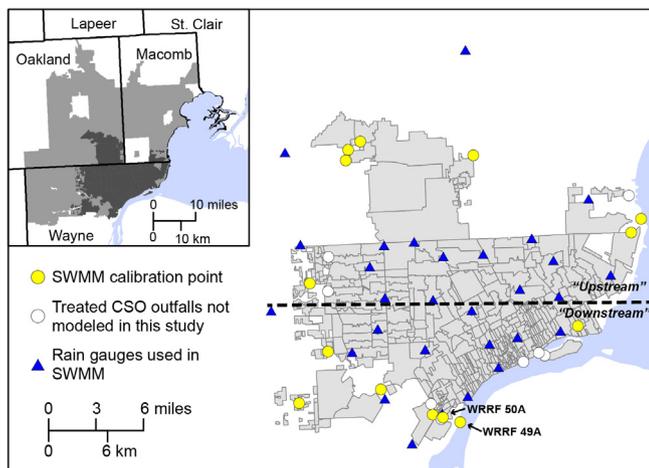


Fig. 2. Inset map: GLWA sewer service area, with the separate sewer area shown in lighter gray and the combined sewer area shown in darker gray. Main map: Area modeled by SWMM. Gray lines delineate the 402 model subcatchments. Yellow circles represent the calibrated outfalls, from which measurements of CSO discharges were used to calibrate SWMM; we present results for these outfalls only. White circles are other treated CSO outfalls that were not modeled in this study. Triangles are rain gauges used in SWMM simulations. Dashed black line separates “upstream” and “downstream” outfalls referenced in results. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

stant CSO TP concentration. Four modeling exercises were conducted, as described below. For each exercise, we ran the model with both representative rainfall (based on April 1–30, 2014, when about 2 in. (50.8mm) of rain fell), and an extreme rainfall case from August 11–12, 2014, when over 6.5 in. (165.1mm) of rain fell. This corresponds roughly with a 500 year return period and is the second highest recorded rainfall event in Detroit (National Weather Service, 2014). We allowed rainfall to fall evenly across the system (see rain gauge locations in Fig. 2) to generate comparable results for all RTBs. All twelve RTBs had overflow events under the heavy rainfall case, but only four did during the representative case. When calculating percent reductions in CSOs, the baseline volumes were those generated by the model for these representative and extreme events.

Disconnection analysis

To determine which subcatchments are influential on CSO discharges at each of the 14 outfalls (Fig. 2) and for the total sewer collection system, we eliminated rainfall over one subcatchment at a time in SWMM and calculated the resulting percent reduction in CSO volumes (see equations in ESM Appendix S1 for Disconnection Analysis). This is analogous to disconnecting a subcatchment from the system, which in the real world would entail converting it to a separate stormwater system.

Pervious land cover analysis

Land use is one of the base inputs of SWMM. To explore the impact of increasing pervious land cover, we adjusted the land use input by increasing the fraction of pervious cover by 5%, 10%, 15%, and 20%, and for each increment we calculated the percent reduction in CSO volume at each outfall and for the entire system. The baseline fraction of pervious surface for each subcatchment was estimated from the National Land Cover Database (2011). The above percentages are equivalent to roughly 29 km², 58 km², 86 km², and 115 km². While this may not be a realistic range, it

provides an understanding of the potential impacts, or lack thereof, on CSOs derived from increasing pervious land.

Green infrastructure tests

There are many green infrastructure (GI) modules built into SWMM that can be implemented for scenario studies. We assessed the effects of two common types of GI: bioretention cells and permeable pavement, chosen based on input from the larger project’s 30-member advisory group that included representatives from state, provincial, and federal agencies; the agricultural community; environmental NGOs; and academia (Scavia et al., 2019b). Underdrains were modeled as part of both GI types to comply with local soil conditions. We increased coverage of each GI type from 0% to 20% of the combined sewer region to generate response curves for percent change in CSO volume at each outfall and for the entire system. As with the pervious land cover exercise, these response curves are intended to provide an understanding of the range of potential impacts GI may produce. Additional details of the model parameters used for the GI scenarios are provided in ESM Table S4.

Results

Urban TP contributions

The three urban areas together contribute 583 metric tons per annum (MTA) of TP to the watershed (water year 2013–2016 average), with point sources making up most (81%) of the load, followed by 10% from runoff and 9% from CSOs (Fig. 3). Roughly 88% of this load came from the Michigan study area, with most of that (56% of the urban TP) from the WRRF, even though it decreased its load from 672 MTA to 331 MTA (51% decrease) between 2008 and 2016 (Fig. 4). Note that the decreases from the WRRF mainly occurred between 2008 and 2012, in contrast with less than 4% variation of TP loads between 2013 and 2016 (ESM Table S5). On average, the Michigan urban study area contributes 37% of the phosphorus load from the watershed (1400 MTA; Scavia et al., 2019a), and the WRRF is 23% of the watershed load. Windsor and London contributed only 12% of the urban TP load (69 MTA from both regions together), and 5% of the total watershed load.

Sanitary sewer overflows (SSOs), which occur when water volumes overwhelm separate sewer systems, are also often a concern for local communities because they contaminate water with raw sewage. They were not considered in the final results of this study, though, because their locations and TP concentrations are not systematically recorded, and because their estimated TP contribution

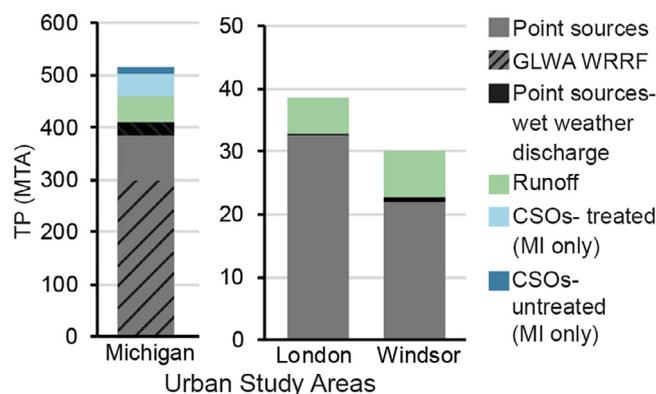


Fig. 3. Urban TP loads (MTA) from point sources, combined sewer overflows, and runoff from the three urban study areas for the study period (2013–2016).

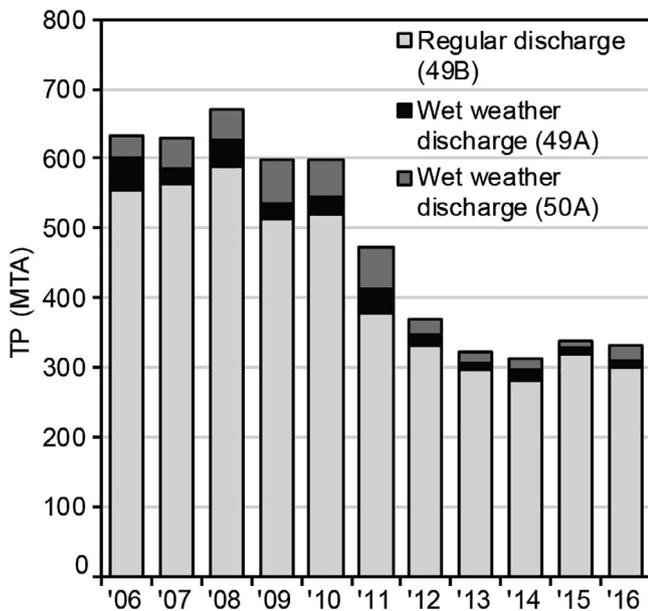


Fig. 4. Annual (water year) TP loads discharged from the GLWA WRRF in Detroit. Regular, dry-weather discharge (light gray bars) and wet-weather discharge (darker gray bars) are both shown. Outfall numbers are indicated in parentheses. The WRRF has two separate wet weather outfalls, one to the Rouge River and one to the Detroit River.

is very small compared to the other sources. We summarized the total SSO volume reported for Macomb, Oakland, and Wayne counties in Michigan for 6 years (see ESM Appendix S1 for SSO Analysis) and found an average annual discharge volume of 829 million gallons (3124 million liters); the WRRF treats 650 million gallons (2460 million liters) each day, so it can be concluded that the SSO contribution is not influential to the total urban load.

Our analysis shows that annual wet-weather related (including CSOs and wet-weather from the WRRF) TP loads were significantly positively correlated ($R = 0.67$, $p = 0.025$) with rainfall (Fig. 5). We would expect that rainfall would not explain all of the variations in the data, because operational controls of RTBs and sewer system flows also can impact whether CSOs occur. This is especially true at shorter time scales; while we observed a significant relationship for annual loads, on a daily or weekly basis, results may be differ-

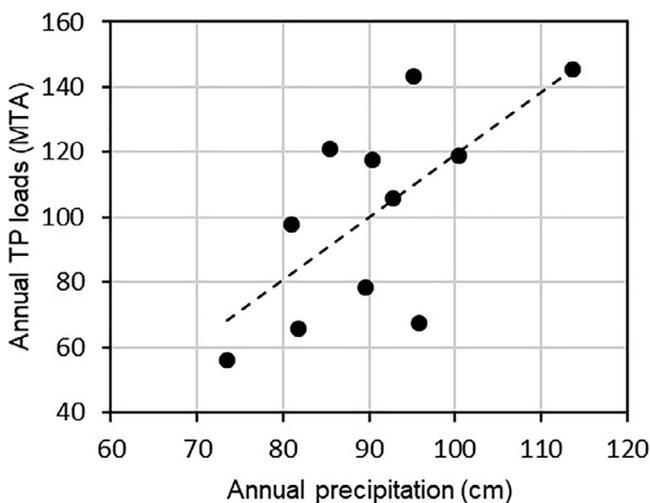


Fig. 5. Relationship between annual precipitation and total TP loads from wet-weather related discharge (including CSOs and wet-weather from the WRRF) in the Michigan urban study area (shown in Fig. 1B).

ent. SWMM modeling results, discussed below, provide further information on dynamics at these shorter time scales.

CSO subcatchment impacts

From the subcatchment disconnection analysis conducted using SWMM, we found that CSOs at upper outfalls in the system are clearly influenced by their adjacent and nearby subcatchments. Removing rainfall into those subcatchments caused substantial reductions in these “upstream” CSOs. Removing rainfall from nearby subcatchments did not have a large impact on reducing CSOs lower in the system, however.

For the wet weather discharge from the entire system, including outfalls at the WRRF, the model indicated that nearly all individual subcatchments had some influence on discharge, and no single subcatchment disconnection had a large impact. We divided the volumetric contribution of each subcatchment by its impervious area to get the reduction potential per unit impervious area (Fig. 6) and found that downstream subcatchments and those that are not controlled by RTBs may be somewhat more influential on reducing total wet weather discharge (i.e., disconnecting them may result in a greater reduction in wet weather discharge across the system). However, the impact of any given single subcatchment is still small.

Pervious land cover

Under representative rainfall conditions, increasing pervious land cover substantially reduced upstream CSO volumes; a 5% increase in pervious cover reduced those CSOs by over 20% on average (Fig. 7). Downstream impacts were smaller, but still substantial; a 5% increase in pervious cover reduced these by about 10% on average. However, impacts at the WRRF and for the system overall were limited under the representative rainfall scenario.

Under the extreme storm scenario, CSO reductions were minimal at both upstream and downstream outfalls (Fig. 7). Increasing the amount of pervious land by 5% resulted in only 2–3% CSO reduction at each subcatchment. Wet weather discharge volumes

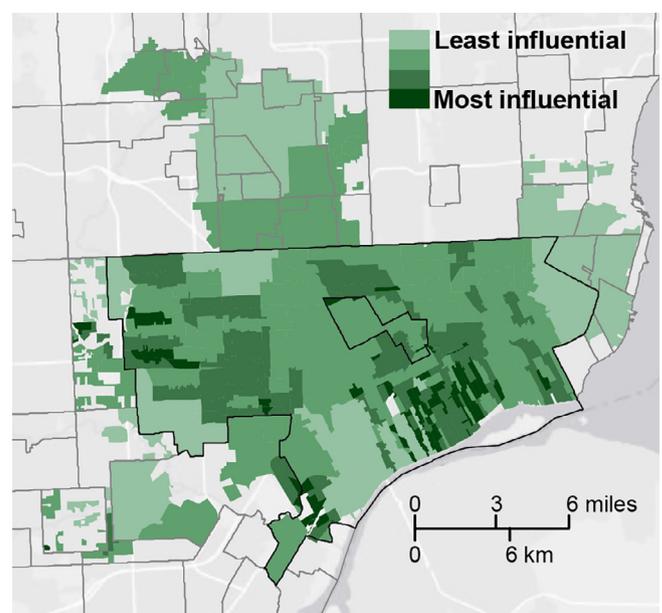


Fig. 6. Relative area-weighted influence of each subcatchment on total wet-weather discharge reduction from the system. Four colors are shown, corresponding to lower (light shading) and upper (dark shading) quartiles of the data. Black line marks the Detroit city boundary.

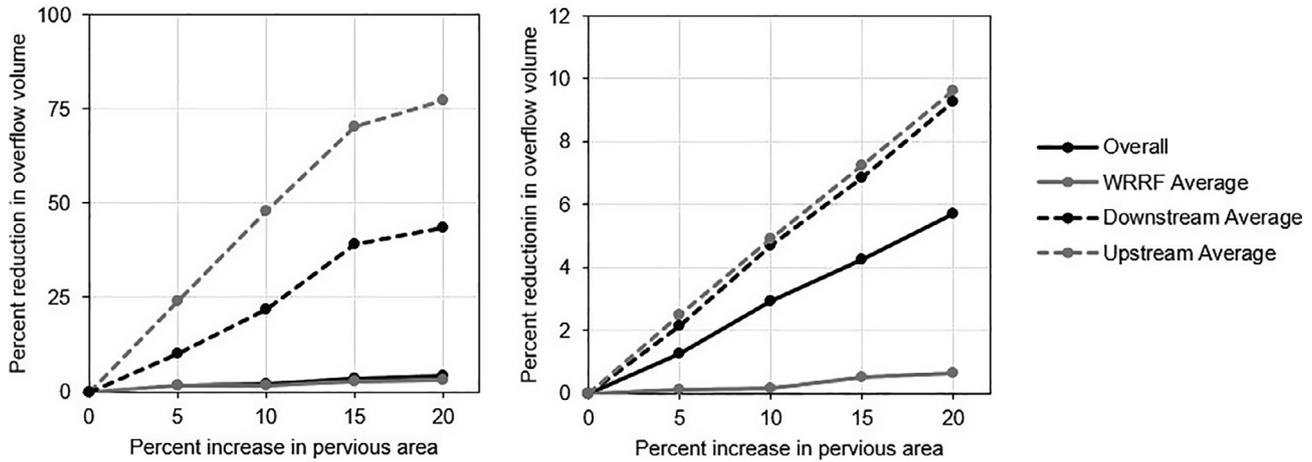


Fig. 7. Percent reductions in CSOs/wet weather discharge as a result of increasing pervious land cover throughout the combined sewer system area under representative (left) and extreme (right) rainfall conditions. Note the different scales on the y-axes.

for the whole system decreased by only about 1% with a 5% increase in pervious land cover, and an increase in pervious land cover of 20% resulted in a wet weather decrease of only about 6%.

Green infrastructure

Simulations of the two green infrastructure implementations generally followed similar outcomes to increases in pervious area

(Fig. 8). Only one upstream location actually had an overflow under representative rainfall conditions. As such, placement of GI showed the potential to entirely reduce upstream CSOs under those conditions. Downstream CSOs were less affected by GI placement, but still showed reductions under representative rainfall, and the system as a whole showed CSO reductions of 16–18% with maximal GI coverage. Under extreme rainfall conditions, all of the locations had CSO events, and the system as a whole showed a maximum

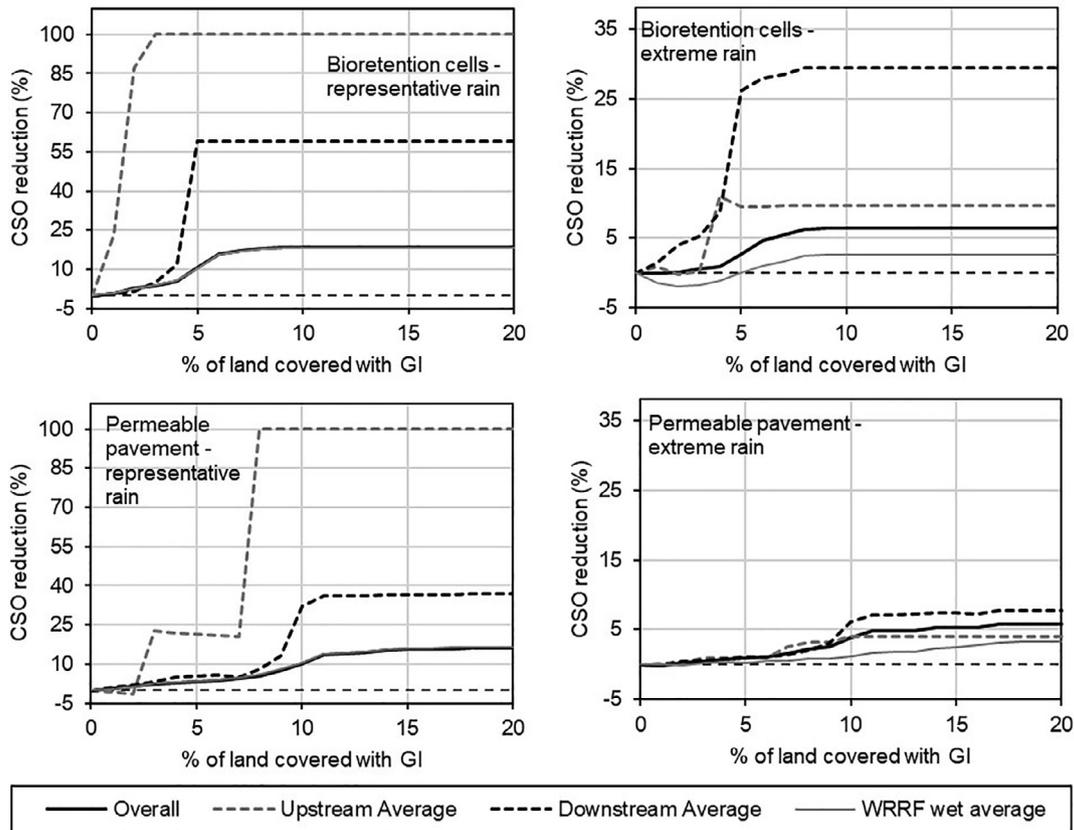


Fig. 8. Reduction in wet-weather/CSO discharges under representative (left column) and extreme (right column) rainfall scenarios with implementations of bioretention cells (top row) and permeable pavement (bottom row). Note the different scales on the y-axes between the left and right columns. Under representative rainfall conditions, only one upstream RTB and three downstream RTBs had overflow events. Horizontal dashed line represents zero reduction; note very small negative reductions (i.e., increases in CSO) at low percent implementations of GI in some cases. Under representative rain, the overall reductions were essentially the same as the WRRF wet weather reductions, and the lines on the plot overlap.

reduction of about 6% with both GI types. In addition, CSO reduction downstream was larger in comparison with higher CSO reduction upstream under representative rainfall conditions. As would be expected given storage volume and cell dynamics, bioretention cells generally performed better than permeable pavement at reducing CSOs. At some upstream RTBs, however, under the extreme rainfall scenario, CSO volumes actually increased as the coverage of bioretention cells increased up to 5%. This is because bioretention cells hold back water and release it gradually through an underdrain. In some cases this may shift bioretention outflows into the peak of the hydrograph, rather than attenuating peak flows.

Discussion

Overall, 81% of urban TP loads resulted from point sources, with no more than 3% variation between 2013 and 2016 (ESM Table S5). As such, only relatively subtle inter-annual variability was noted in total urban TP loads discharged to the St. Clair-Detroit River System. Average values were thus used to indicate the contributions of urban TP loads from various sources (Fig. 3). Between 2013 and 2016, these three urban areas currently contribute, on average, 583 MTA of TP, or 42% of the total load from the St. Clair-Detroit River watershed (1400 MTA; Scavia et al., 2019a), with 88% of the urban load coming from the Michigan urban study area, and 56% of the urban load from the WRRF. While London or Windsor may have local water quality concerns and reasons to reduce TP loads, these reductions will only have small impacts at the watershed scale. There are other smaller urban areas within the watershed as well, such as Chatham-Kent, ON and Port Huron, MI, but given that we determined that Windsor is the third largest urban area in the watershed and it contributes less than 2% of the Detroit River's load to Lake Erie, we can conclude that other urban regions have minor impacts relative to the overall TP load. Similarly, while efforts to reduce CSOs will not have large impacts on the TP delivered to Lake Erie from the Detroit River, CSO mitigation is often a priority for local communities and municipal governments due to public health concerns linked to other pollutants present in wastewater.

While still the main contributor to the watershed's urban TP load, the WRRF load decreased significantly since 2008 (Fig. 4) due primarily to improvements in chemical and biological technologies of phosphorus removal (Khan et al., 2018). The average TP concentration in dry-weather discharge decreased from 0.67 mg/L prior to the improvements (i.e., over the years 2006–2010) to a 2013–2016 average of 0.38 mg/L, far below the permitted limit which varies seasonally between 0.6 and 0.7 mg/L. The population served by the facility decreased only slightly (by 4.2%) between 2000 and 2009 and 2010–2016 (see ESM Appendix S1 for Population Analysis), confirming the reduction was primarily due to improved treatment. However, the facility still currently contributes 13% of the total phosphorus load to the Detroit River (2425 MTA; Scavia et al., 2019b), and any further improvements to the treatment process would provide a centralized and high-impact means to reduce loads. While non-trivial in technological, human resource, and financial costs, improving treatment operations could potentially have one of the biggest, centralized impacts on reducing the urban phosphorus load.

Given annual wet-weather related TP loads were highly correlated with annual rainfall (Fig. 5), one would expect that increasing pervious surfaces would reduce CSO discharges because more of the rainfall would be absorbed in the ground. But, the results from our SWMM analysis showed that a 10% increase of pervious area across the entire combined sewer area, an area equivalent to about 58 km², decreased total CSO discharges less than 3% under the

extreme storm scenario (Fig. 7). This is likely because much of the soil in the area has low infiltration capacity (USDA Soil Survey, 2018), and can thus be quickly saturated during extreme storms. However, there were substantial reductions at some upstream RTBs, consistent with the disconnection analysis that suggested it may be possible to reduce discharge volumes at upstream RTBs, but making a system-wide impact is much more difficult. Similarly, because runoff is controlled by precipitation and the amount of impervious surface, increasing the amount of pervious surfaces should reduce runoff, though we did not quantify runoff in SWMM.

Our conclusions from our SWMM-based analysis of green infrastructure (bioretention cells and permeable pavement) showed more potential to reduce CSOs under representative rainfall compared to extreme events, and in general upstream CSOs showed larger reductions than downstream CSOs. GI shows promise for reducing local CSOs at upstream catchments under representative rainfall conditions and could play a significant role when focused in these regions (e.g., 100% CSO reduction with less than 5% of land covered with bioretention cells under representative rainfall as shown in Fig. 8). Given the complexity of the collection system, no single solution for reducing CSOs is apparent. The local soil conditions are not amenable to significant infiltration, which means that GI often shifts the timing of the flows without capturing much volume. The benefits of these upstream reductions may become muted downstream, and thus may not play a large role in reducing overall CSOs across the entire system. GI also showed less potential for reducing CSOs under the extreme rainfall case. This likely explains the lower upstream CSO reduction in comparison with the downstream CSO reduction under the extreme rainfall scenario (Fig. 8). While not analyzed here, more classic gray infrastructure solutions, such as extra storage, should be analyzed to determine their ability to complement ongoing GI efforts. We also note that our GI analysis focused solely on CSO reduction and that there are many additional reasons for implementing GI, including enhanced community well-being, impact on non-phosphorus water quality issues, and real-estate and urban habitat enhancement. While beyond the scope of our study, these and other benefits should be weighed as part of a broader GI implementation.

Large collection systems have many infrastructure assets that can 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, enabling the current system to be used more efficiently. This was not evaluated in our study, but recent simulation studies (Wong and Kerkez, 2018; Kerkez et al., 2016) show promise in applying such "smart" and autonomous solutions (e.g., open-storm.org).

Our subcatchment-influence, perviousness analyses, and GI tests provide an assessment of the potential impacts of improved land cover and soil conditions. While they do not provide realistic guides for implementation of management options, they provide baseline assessments of which subcatchments may be influential to CSOs at specific locations. The analyses all speak to the complexity of this system. Improvements are expected to result in local benefits, primarily at "upstream" locations and during normal rain, but as flows combine, benefits are obscured and tapered in the lower reaches of the service area, and when storms are large it may be more difficult to achieve reductions.

In conclusion, while the main contributor to the watershed's urban TP load is the WRRF in Detroit, its load has decreased by over half since 2008. Further reductions are possible, but likely expensive under current technologies. Because CSO contributions are a relatively small contribution to the overall load, efforts to reduce them will not have large impacts on the TP delivered to Lake Erie. However, CSO mitigation is often a priority for local communities

and municipal governments. Our results showed that GI may be effective in mitigating CSO discharges under average storms, in particular in the upstream regions. Overall, however, a balanced portfolio of stormwater management and treatment options will ultimately be needed to address system-scale TP reduction.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jglr.2019.09.009>.

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