Urban Total Phosphorus Loads to the St. Clair-Detroit River System

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- Phosphorus
- Urban loads
- Detroit River
- SWMM

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 model 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 decreased by about 51% since 2008 through 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 for total wet-weather discharge from the system.

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; Ludsin 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, Bocaniov et al. in review, Dagnew et al. 2019a,b) as part of an integrated assessment of its phosphorus sources and loads (Scavia et al. 2019b; myumi.ch/detroit-river). 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 km^2 St. Clair-Detroit River watershed (Figure 1) that contains both large urban areas and extensive agricultural. 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. (2019 a,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 watersheds dominated by agricultural inputs (Kalmykova et al., 2012), despite a finding by Hobbie et al. (2017) that only 22% of net P inputs to urban areas are retained, with the rest flushed to waste- and storm-water drains and ultimately discharged to water bodies. Herein, we focus on 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 (Figure 1). Quantifying these loads can help determine where reductions could be made and where reduction efforts may only have limited impacts. Our study objectives were to quantify the TP loads from the different types of urban sources, determine the factors that contribute to load variability, and explore load reduction scenarios.

METHODS

Study Areas - To delineate major urban areas, we selected subbasins (HUC-12) with more than 80% urban land cover in the US (NASS CDL, 2016), and more than 60% in Canada (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 (Figure 1). The Michigan urban study area (Figure 1b) covered 2,390 km^2 and contained over 3.1 million people, while Windsor (Figure 1c) and London (Figure 1d) study areas were 149 km^2 and 138 km^2, respectively, with populations of about 211,000 and 366,000.

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 (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 (Figure 1b, Table S2) that are permitted to release phosphorus to surface water and that had discharge events during our study period. 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 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. 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 (available at https://echo.epa.gov/resources/general-info/loading-tool-modernization), and Windsor and London data were obtained from Ministry of the Environment and Climate Change (MOECC) (https://www.ontario.ca/data/industrial-wastewater-discharges).

Combined Sewer Overflows - The Michigan urban study area contains 26 treated and 78 untreated CSO outfalls (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 treated outfalls operated by GLWA (n=7), 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 (https://www.deq.state.mi.us/csosso) and monthly TP concentrations were retrieved from the EPA ECHO database. If the concentration data were missing, 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 based on measured TP concentrations of inflow to the WRRF. This is may be a conservative estimate, because TP loads in untreated CSOs can vary based on factors such as duration of discharge and antecedent weather conditions.

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 OMECC (Dong Zhang, OMECC, personal communication), but concentration measurements were not available. Since wet-weather flow usually receives primary treatment before it is discharged, we used the median TP concentration from discharges from the RTBs operated by GLWA for load calculations (0.67 mg/L).

Runoff Contributions - A regression model (Arnold et al., 2012; Tasker & 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 (https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/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 were calculated from the National Land Cover Database (2011). We used the regression model to calculate both upper and lower estimates for TP from runoff (SI: 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 - We used a previously calibrated Storm Water Management Model (SWMM) to simulate the combined sewer area in metro Detroit (Figure 2). The model was calibrated to volume discharge measurements at 12 retention basis, the two wet-weather outfalls at the WRRF, and for inflow to the WRRF (Hu et al., 2018). The model is based on 402 subcatchments with unique land cover, soil, gray infrastructure, and connectivity to the sewer system. 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 inches of rain fell), and an extreme rainfall case (based on an event from August 11-12, 2014, when over 6.5 inches of rain fell). We allowed rainfall to fall evenly across the system (see rain gauge locations in Figure 2) to generate comparable results for all RTBs. All 12 RTBs had overflow events under the heavy rainfall case, but only 4 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 calibrated outfall 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 SI: Disconnection Analysis). This is analogous to disconnecting a subcatchment from the system, which in the real world would entail converting it to a separated 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 km^2, 58 km^2, 86 km^2, and 115 km^2. While this may not be a realistic range, it provides an understanding about 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 advisory group (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 about the range of potential impacts GI may produce. Additional details of the model parameters used for the GI scenarios are provided in 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 (Figure 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 from 672 MTA to 331 MTA (51% decrease) between 2008 and 2016 (Figure 4). 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 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 (SI: SSO Analysis) and found an average annual discharge volume of 829 million gallons; the WRRF treats 650 million gallons each day, so it can be concluded that the SSO contribution is not influential to the total urban load.

Our analysis show that annual CSO TP loads were significantly positively correlated (R=0.67, p=0.025) with rainfall (Figure 5). We would expect that rainfall would not explain all of the variation 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 different. 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 outfalls higher 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 as large an 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 weighed the reduction potential of each subcatchment by its impervious area (Figure 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. 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 (Figure 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 (Figure 7). Increasing the amount of pervious land by 5% resulted in only 2-3% CSO reduction at each basin. Wet weather discharge volumes 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 (Figure 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 impacted 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 reduction of about 6% with both GI types. As would be expected given storage volume and cell dynamics, bioretention cells generally performed better than permeable pavement at reducing CSOs. At some RTBs, however, under the extreme rainfall scenario, CSO volumes actually increased as the amount of GI increased up to 8%. 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

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 55% of the urban load from the WRRF. So, 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 often a priority for local communities and municipal governments because they can present public health concerns due to other pollutants present in wastewater.

While still the main contributor to the watershed's urban load, the WRRF load decreased significantly since 2008 (Figure 3) due primarily to improvements in treatment technology. 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 2000-2009 and 2010-2016 (SI: 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. With treatment processes and technologies continually developing, it is could be possible for some advances to be implemented in the future.

Because annual CSO TP loads were highly correlated with annual rainfall (Figure 5b), 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 previous area across the entire combined sewer area - an area equivalent to about 58 km^2 - decreased total CSO discharges less than 3%. This is likely because much of the soil in the area has low infiltration capacity (USDA Soil Survey, 2018). However, there were substantial reductions at some upstream RTBs, consistent with the disconnection analyses 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. 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. 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 nonphosphorus 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 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 are may be influential to CSOs at specific locations. The analyses both 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 services area, and when storms are large it may be more difficult to achieve reductions.

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Figure Legends

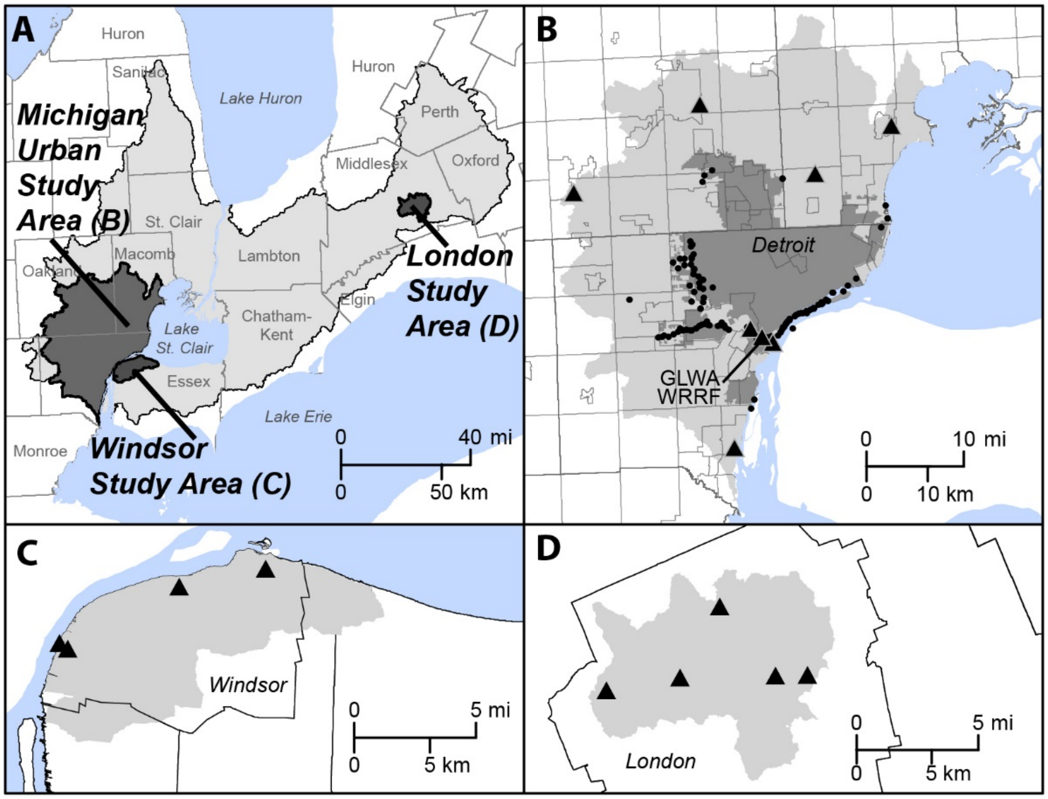

Figure 1:

(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.

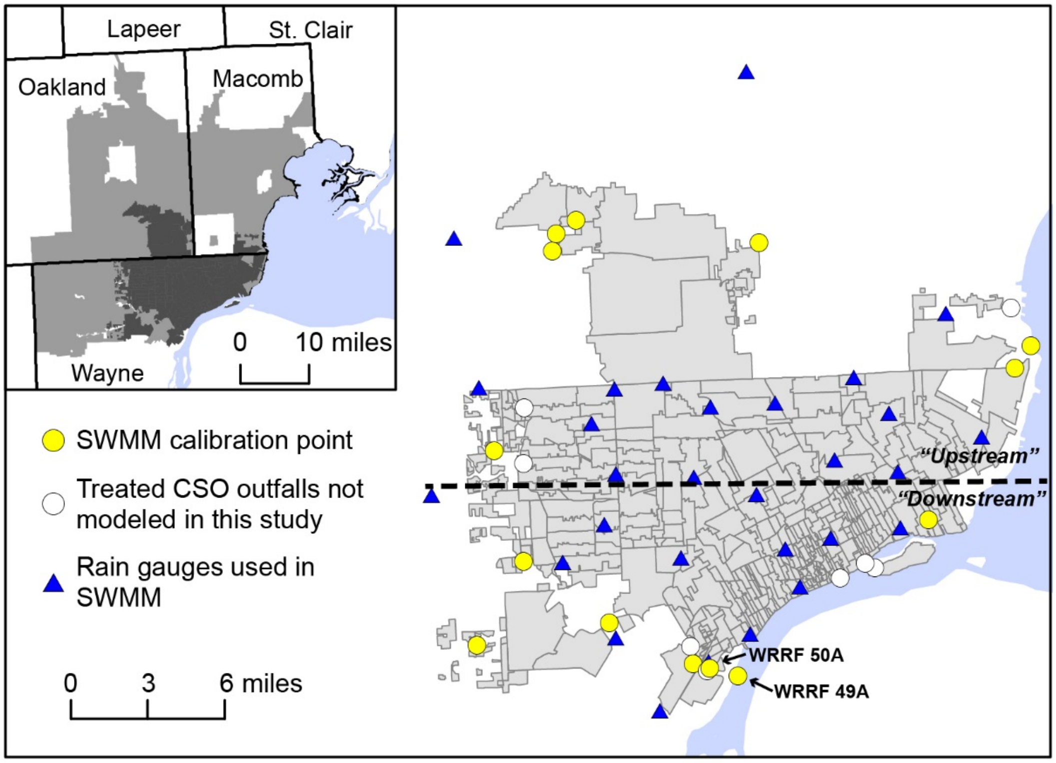

Figure 2. Inset map: GLWA sewer service area, with the separated sewer area shown in lighter gray and the combined sewer area shown in darker gray. Main map: Area modeled by SWMM. Gray lines delineate the 402 model subcatchments. Yellow circles represent calibrated outfalls; we present results for these 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.

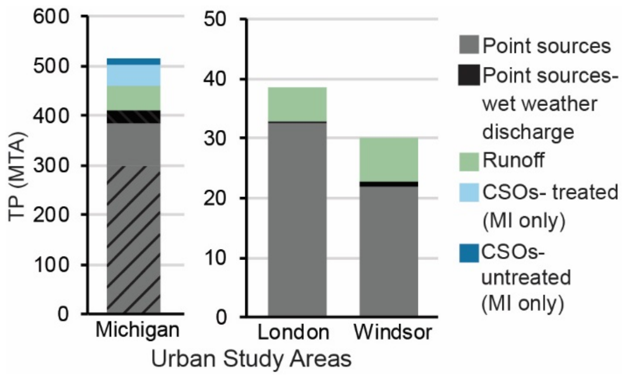

Figure 3: Urban TP loads (MTA) from point sources, combined sewer overflows, and runoff from the three urban study areas.

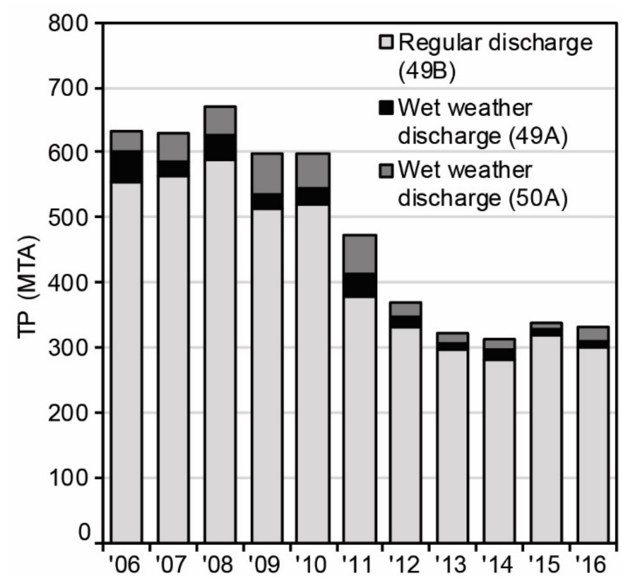

Figure 4. Annual (water year) TP loads discharged from the GLWA WRRF in Detroit. Regular, dry-weather discharge (light gray bars) and wet-weather discharge (darker gray bars) are both shown.

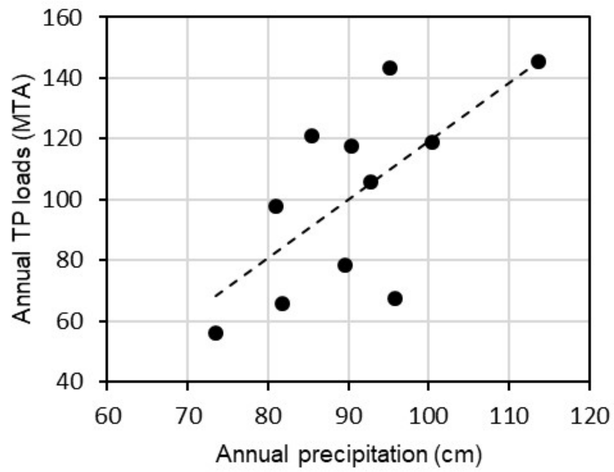

Figure 5. Relationship between annual precipitation and total TP loads from wet-weather discharge (including CSOs and wet-weather from the WRRF).

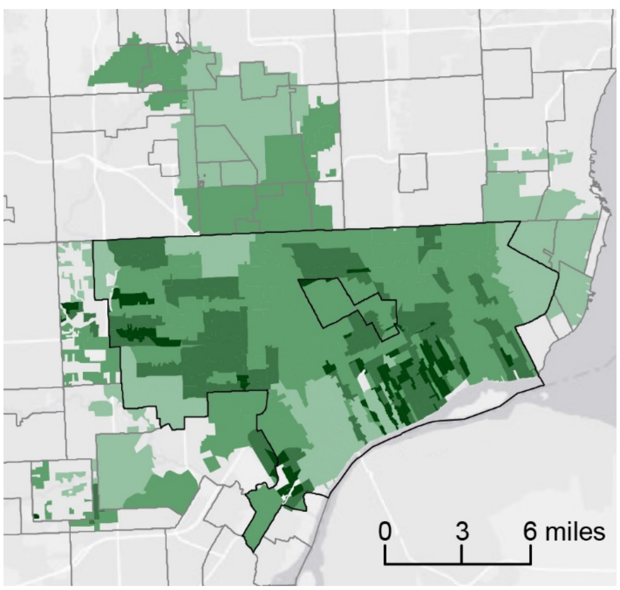

Figure 6. Relative area-weighted influence of each subcatchment on total wet-weather discharge for the system. Four colors are shown, corresponding to lower (light shading) and upper (dark shading) quartiles of the data. Black line marks the Detroit city boundary.

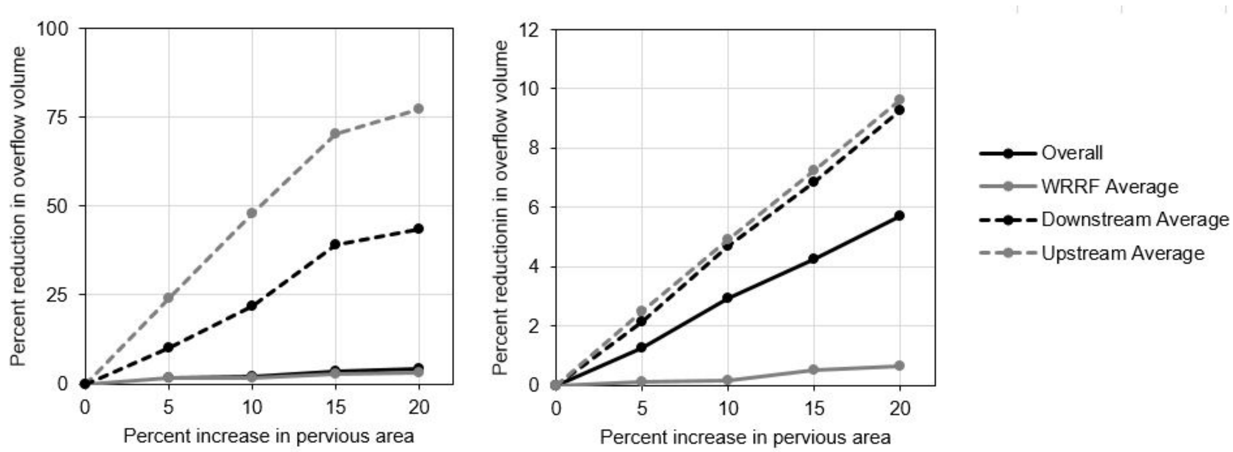

Figure 7. Percent reductions in CSOs/wet weather discharge as a result of increasing pervious land cover throughout the combined sewer system area under representative (left) and extreme (right) rainfall conditions. Note the different scales on the y-axes.

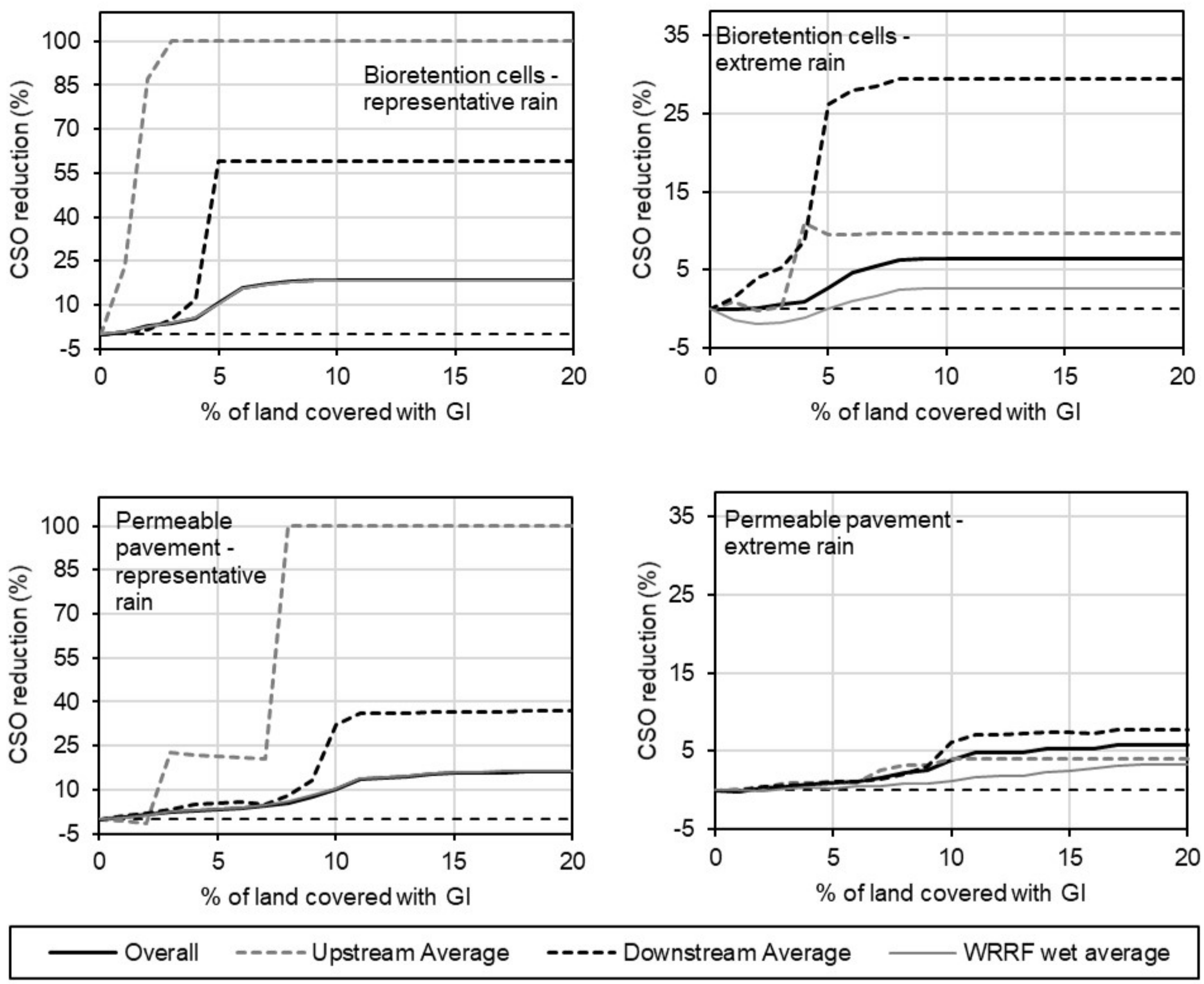

Figure 8. Reduction in wet-weather/CSO discharges under representative (left column) and extreme (right column) rainfall scenarios with implementations of bioretention cells (top row) and permeable pavement (bottom row). Note the different scales on the y-axes between the left and right columns. Under representative rainfall conditions, only one upstream RTB and three downstream RTBs had overflow events. Horizontal dashed line represents 0 reduction; note very small negative reductions (i.e., increases in CSO) at low percent implementations of GI in some cases.