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Detroit River phosphorus loads: Anatomy of a binational watershed

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ABSTRACT

As a result of increased harmful algal blooms and hypoxia in Lake Erie, the US and Canada revised their phosphorus loading targets under the 2012 Great Lakes Water Quality Agreement. The focus of this paper is the Detroit River and its watershed, a source of 25% of the total phosphorus (TP) load to Lake Erie. Its load declined 37% since 1998, due chiefly to improvements at the regional Great Lakes Water Authority Water Resource Recovery Facility (WRRF) in Detroit and phosphorus sequestered by zebra and quagga mussels in Lake Huron. In addition to the 54% of the load from Lake Huron, nonpoint sources contribute 57% of the TP load and 50% of the dissolved reactive phosphorus load, with the remaining balance from point sources. After Lake Huron, the largest source is the WRRF, which has already reduced its load by over 40%. Currently, loads from Lake Huron and further reductions from the WRRF are not part of the reduction strategy, therefore remaining watershed sources will need to decline by 72% to meet the Water Quality Agreement target - a daunting challenge. Because other urban sources are very small, most of the reduction would have to come from agriculturally-dominated lands. The most effective way to reduce those loads is to apply combinations of practices like cover crops, buffer strips, wetlands, and applying fertilizer below the soil surface on the lands with the highest phosphorus losses. However, our simulations suggest even extensive conservation on those lands may not be enough.

Introduction

Among the Laurentian Great Lakes, Lake Erie is the warmest, shallowest, and most productive, contributing to its sensitivity to nutrient inputs. In the 1960s and 70s, increasing phosphorus inputs led to severe algal blooms in its western basin and extensive periods of low oxygen (hypoxia) in the bottom waters of its central basin. Phosphorus abatement programs, initiated in response to the 1972 Great Lakes Water Quality Agreement (GLWQA), prompted wastewater treatment facilities to add secondary treatment, removed phosphorus from most soaps and detergents, and enhanced land conservation programs, resulting in substantial water quality improvements (DePinto et al., 1986, Ludsin et al., 2001).

However, in the mid-1990s, harmful algal blooms and hypoxia returned to conditions similar to the 1960s and 70s (Scavia et al., 2014). Results from a synthesis of models (Scavia et al., 2016) showed that the increasing spring load of dissolved reactive phosphorus (DRP) from the Maumee River was the primary driver of the western basin blooms (Bridgeman et al., 2013, Michalak et al., 2013, Scavia et al., 2014, 2016; Obenour et al., 2014, Stumpf et al., 2016; Bertani et al., 2016) and that temperature and annual load of total phosphorus (TP) to the western and central basins was the primary driver of hypoxia (Del Giudice et al., 2018, Zhou et al., 2015, Rucinski et al., 2014, 2016; Bocaniov et al., 2016).

In 2012, the US and Canada revised the GLWQA, calling for new Lake Erie phosphorus loading targets and associated action plans. In response to this commitment, they adopted the following targets, each compared to a 2008 baseline (GLWQA, 2016).

- For central-basin hypoxia, a 40% reduction in the western and central basin TP load.

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- For 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).
- For western-basin algal blooms, a 40% reduction in Maumee spring TP and DRP loads.

US and Canadian domestic action plans placed substantial attention on loads from Detroit and Maumee rivers because they 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). The plans were developed within adaptive management frameworks and the initial phase of review and potential adaptation is underway in 2019.

There have been 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., 2016, Kalcic et al., 2016). However, the sources of nutrients contributing to the Detroit River load have been somewhat uncertain due to limited data and an historical lack of attention to its watershed, which includes both intensive agriculture and major urban areas. This river system is also complicated by the presence of the large, shallow Lake St. Clair, which processes the nutrient load from its 15,000 km^2 watershed, as well as from the St. Clair River. Whether the lake is an ultimate source of, or sink for, phosphorus, and whether loads from its different tributaries (e.g., Clinton, Sydenham, Thames, St. Clair rivers) have equally significant impacts downstream, has been unclear. It has also been difficult to measure the Detroit River load accurately because it is not well mixed in transverse direction to flow, requiring extensive sampling across the river and over time, and because Lake Erie storm surges and seiches occasionally can push lake water into the river (Derecki and Quinn, 1990), introducing large uncertainties and hampering estimates of river discharge and nutrient load.

Understanding nutrient sources is critical for developing load reduction plans and for deciding the level of emphasis that should be placed on different tributaries or different source types (e.g., point sources, agricultural runoff). To help reduce these uncertainties, this project set the following objectives with the help of stakeholders from the public and private sectors: 1) estimate how different sources contribute to the Detroit River phosphorus load to Lake Erie, and 2) evaluate options for reducing those loads.

Methods

Study region

The St. Clair-Detroit River system (Fig. 1) receives water and nutrients from Lake Huron and the 19,040 km^2 watershed that covers parts of southeastern Michigan (40% of watershed area) and southwestern Ontario (60% of watershed area). It delivers nutrients to Lake Erie through the Detroit River. The Detroit River provides approximately 80% of the water flow into Lake Erie and 25% of the lake's annual TP inputs, and its phosphorus concentrations are relatively low compared to the Maumee River. Because of the low concentrations and high flow, it tends to dilute nutrients in the western basin, creating a zone where the Detroit River and the western basin water mix, and algae and total suspended solids concentrations are low (Electronic Supplementary Material (ESM) Fig. S1). However, the river's annual TP load contributes significantly to central-basin algal production and ultimately to the extent of hypoxia there.

The watershed is composed of about 49% cropland, 21% urban area, 13% forest, 7% grassland, and 7% water bodies (Dagnew et al., 2019a). Overall, 79% of the watershed's agricultural land is in Canada and 83% of the urban land is in the US. The Clinton and Rouge sub-watersheds are heavily urbanized (about 56% and 89% urban, respectively), whereas the St. Clair, Sydenham, and Thames sub-watersheds are dominated by agriculture (63%, 89%, and 87%, respectively).

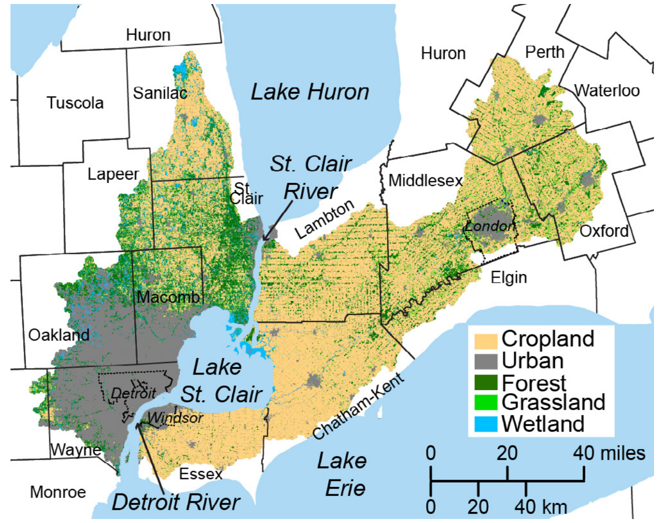

Fig. 1. Land use in the St. Clair-Detroit River System watershed. The watershed is composed of about 49% cropland, 21% urban land, 13% forest, 7% grassland, 7% surface water (including Lake St. Clair), and 3% wetlands.

The US portion of the watershed has three sub-watersheds (St. Clair, Clinton, and Rouge) drained primarily by the Black, Clinton, and Rouge rivers, respectively. These sub-watersheds often include multiple drainage areas. For example, in addition to the Black, the St. Clair sub-watershed includes the Pine and Bell river systems (see Fig. 9 below), and the Rouge sub-watershed includes the Rouge River system as well as land that drains directly in the Detroit River. The Canadian portion of the watershed has three tertiary watersheds (Upper Thames, Lower Thames, and Sydenham) drained by the Thames and Sydenham rivers. The study region also includes the Essex watershed in Canada and the Lake St. Clair watershed in the US.

Five of the six sub-watersheds drain into the 1,115 km^2, 4.25 km^3 Lake St. Clair (ESM Fig. S2), a shallow, polymictic lake with a mean depth of 3.8 m, a maximum natural depth of 6.5 m, and an 8.2 m deep navigation channel (Bocaniov and Scavia, 2018). It 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. While the lake's theoretical flushing time is roughly 9 days, that flushing time varies seasonally and, more significantly, spatially (Bocaniov and Scavia, 2018) such that during summer, water in the south-eastern part of the lake flushes more slowly than the north-western part. This, in combination with different timing and magnitude of tributary loads, leads to spatial segmentation of primary production resulting in the northwest part of the lake being oligotrophic and southeast part mesotrophic.

As part of this assessment, three urban regions received special focus. The National Land Cover Database (NLCD, 2011) and the Annual Crop Inventory (Agriculture and Agri-food Canada, 2016) were used to select HUC-12 subbasins with more than 80% urban land cover in the US and more than 60% in Canada (Hu et al., 2019). This resulted in study areas in southeast Michigan and around London, Ontario and Windsor, Ontario (Fig. 2), and more accurately captured urban areas than using political boundaries. The Michigan urban study area covered 2,390 km^2 with over 3.1

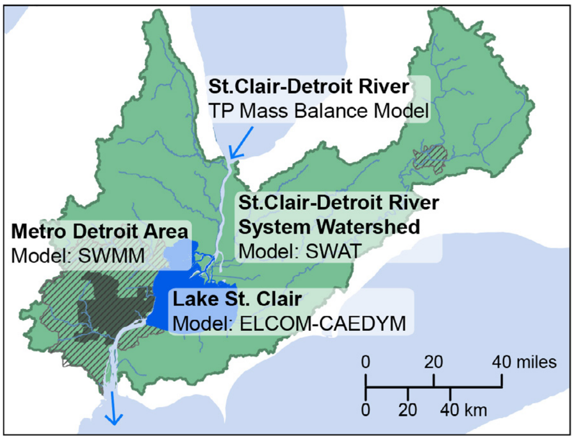

Fig. 2. The four models used in this study. Areas with diagonal lines are the study areas for the analysis of urban sources.

million people. It includes the Great Lakes Water Authority's Water Resource Recovery Facility (GLWA WRRF), one of the largest wastewater treatment facilities in the world, treating sewage from 3 million residents across 77 communities, as well as storm water from the region's combined sewer system. The Windsor and London areas cover 149 km^2 and 138 km^2, respectively, with populations of 211,000 and 366,000.

Models

The assessment was built on the construction and use of four models (Fig. 2) that collectively simulate the dynamics of this complex watershed.

- A nutrient mass balance model based on a closed water budget and accounting for all phosphorus inputs and outputs on a water-year annual basis between 1998 and 2016 (Scavia et al., 2019a), and an accounting of phosphorus sources from within the three major urban areas (Hu et al., 2019).
- A watershed model simulating flow and dynamics of water, nutrients, and sediment on daily-to-annual time scales for 2001–2015, based on the Soil and Water Assessment Tool (SWAT) (Dagnew et al., 2019a).
- A 3-dimensional (3D) coupled hydrodynamic and ecological model of Lake St. Clair (ELCOM-CAEDYM) simulating thermo- and hydrodynamics, nutrient and algal dynamics for 2009 and 2010 (Bocaniov and Scavia 2018).
- An urban model simulating the Great Lakes Water Authority (GLWA) sewer service area based on the Storm Water Management Model (SWMM) (Hu et al., 2018).

Project guidance

An advisory group was established at the project inception to help understand policy contexts and provide feedback on approach and resulting products. The group included US and Canadian representatives from federal, state, and provincial governments; regional conservation authorities; non-profits; universities; and local organizations actively involved in watershed management, policy development, or research (Scavia et al., 2019b). Through more than a dozen in-person meetings, periodic conference calls, and individual consultations, the 30-person advisory group helped ensure that the research would be credible scientifically, and the results would be relevant and usable for the Great Lakes policy and management communities. Preliminary interviews and ongoing 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 scenario analyses for model analyses (Goodspeed et al., 2018). Although all members of the advisory group had opportunities to comment on project results and research summaries, the content of this paper is solely the responsibility of the authors.

Mass balance estimates

Scavia et al. (2019a) compiled and analyzed data from US and Canadian water quality monitoring programs between 1998 and 2016 (Tables 1 and 2, ESM Fig. S3), and used the Weighted Regressions on Time, Discharge and Season (WRTDS) method (Hirsch et al., 2010) to calculate tributary phosphorus loads based on concentrations and flow data for gauged tributaries. Area-weighted estimates based on nearby streams were used for unmonitored areas prior to adding upstream point sources (see Fig. 9 below). Because WRTDS is not appropriate for the connecting channels (St. Clair and Detroit rivers), their loads were estimated by multiplying flow times concentrations. Atmospheric loads to Lake St. Clair were from Maccoux et al. (2016), and loading from Lake St. Clair shoreline erosion was estimated by multiplying the shoreline length by the annual P loading rate for the Lake St. Clair basin (Monteith and Sonzogni, 1976). Monthly industrial and municipal point source data were collected from US EPA, the Great Lakes Water Authority, and the Ontario Ministry of Environment and Climate Change databases (Scavia et al., 2019a). Urban runoff was calculated based on precipitation and impervious area (Arnold et al., 2012).

Lake St. Clair analysis

Lake St. Clair's annual phosphorus retention estimates were based on the TP and DRP mass balances (Scavia et al., 2019a) for water years 1998–2016. Whole-lake estimates, as well as estimates at smaller spatial and temporal scales for 2009 and 2010 were also based on a three-dimensional ecological model (Bocaniov and Scavia, 2018). In both cases, percent retention was calculated as the sum of all inputs minus outputs, divided by inputs. The previously calibrated, validated, and applied ecological model (Bocaniov and Scavia, 2018) was the Computational Aquatic Ecosystem Dynamic Model (CAEDYM) driven by the 3D hydrodynamic model (Estuary, Lake and Coastal Ocean Model: ELCOM). For this application, the model simulates dynamics of phosphorus, nitrogen, silica, oxygen, carbon, and total suspended solids, and five functional groups of phytoplankton (Bocaniov et al., 2016, Bocaniov and Scavia, 2018). This model was also used to explore the relationship between major tributary loads to the lake and loads leaving the lake.

Watershed analysis

The Soil and Water Assessment Tool (SWAT) was applied to the full watershed to explore options for reducing TP and DRP loads (Dagnew et al., 2019a,b). The watershed was divided into 800 sub-basins, approximately 24 km^2, and each sub-basin was further divided into Hydrologic Response Units (HRUs) corresponded to farm fields (approximately 171 acres (68.4 ha) each), the first time this has been done for a watershed of this size. Given the variability in agricultural management between the US and Canada, the advisory group was engaged extensively over the course of the project to both verify and augment the available data and to provide new data where appropriate (Scavia et al, 2019b). The model was calibrated (2007–2015) and validated (2001–2006) to loads estimated from measurements at the mouths of the six major tributaries (Fig. 3) at daily, monthly, and annual time scales, and then used

Table 1
Total phosphorus load estimates (MTA) from monitored stations. Note minor differences between this table and the one in Scavia et al. (2019a) are due to updates in original sources.

TP (MTA)	From Lake Huron	Into the St. Clair River				Into Lake St. Clair						Into the Detroit River				
Water Year		Black	Belle	Pine	Other	St. Clair River	Clinton	Sydenham	Thames	Other	Atmos + Erosion	Lake St. Clair Outlet	Rouge	GLWAP	Other	Lake Erie Inflow
1998	2261	114	35	24	59	2493	202	230	541	129	85	3062	47	727	120	2871
1999	2096	22	9	3	38	2168	144	103	218	60	72	2722	36	727	98	2522
2000	1944	38	17	9	62	2071	192	285	649	111	91	2531	56	545	110	2340
2001	2599	87	34	24	50	2548	167	155	507	126	75	2447	37	545	109	2294
2002	1959	120	35	24	57	2502	156	206	502	145	85	2590	51	636	120	2495
2003	1386	22	9	2	38	2115	90	104	247	59	92	2380	26	588	94	2369
2004	1333	137	53	39	73	1954	174	306	603	170	73	2476	47	632	118	2562
2005	1405	91	32	22	58	1785	126	218	434	106	64	2467	35	618	123	2645
2006	1331	110	37	26	61	1622	145	198	415	103	81	2388	46	634	123	2652
2007	1162	87	33	23	63	1529	146	246	463	104	68	2304	53	630	129	2659
2008	1083	82	31	21	58	1547	145	210	394	104	72	2246	51	672	128	2703
2009	1137	230	89	68	85	1767	254	312	550	161	82	2403	56	599	128	2989
2010	1076	40	19	10	37	1900	115	98	149	45	67	2272	42	600	98	2838
2011	954	143	54	40	61	1914	189	231	390	136	77	2099	68	472	122	2557
2012	980	42	17	9	43	2034	127	168	263	74	61	2054	43	368	106	2365
2013	914	160	47	34	52	1936	142	165	350	104	76	1890	39	323	96	2031
2014	890	58	22	14	49	1965	144	175	425	115	76	1911	52	313	113	1907
2015	966	46	17	9	41	2072	117	115	241	73	76	1991	39	336	92	1823
2016	1152	79	27	17	40	2307	111	89	265	78	76	2035	36	331	100	2479

Table 2
Dissolved reactive phosphorus load estimates (MTA) from monitored stations.

DRP (MTA)	From Lake Huron	Into the St. Clair River				Into Lake St. Clair						Into the Detroit River				
Water Year		Black	Belle	Pine	Other	St. Clair River	Clinton	Sydenham	Thames	Other	Atmos + Erosion	Lake St. Clair Outlet	Rouge	GLWAP	Other	Lake Erie Inflow
1998		42	13	8	24		30	78	91	24	38		9		46	
1999		12	5	2	18		24	37	31	7	38		7		42	
2000		12	5	2	22		32	74	280	36	38		13		50	
2001		32	13	8	22		29	61	111	35	38		8		46	
2002		32	10	6	27		29	108	126	41	38		12		49	
2003		12	5	1	15		24	18	73	19	38		7		44	
2004		39	15	10	25		30	81	186	53	38		29		56	
2005		29	11	6	25		25	87	122	29	38		9	337	54	
2006		38	13	8	27		27	84	119	27	38		13	360	55	
2007		24	9	5	34		30	152	153	28	38		16	403	58	
2008	488	25	10	5	26	454	31	91	130	28	36	765	17	451	59	837
2009	529	68	26	19	41	513	50	174	221	45	41	836	18	369	61	1071
2010	535	13	6	2	16	502	29	30	48	10	34	810	17	262	47	1127
2011	497	46	17	12	26	494	42	91	154	44	38	769	28	242	58	1067
2012	485	12	5	1	24	505	37	113	114	25	30	777	18	228	53	996
2013	423	52	16	10	24	449	37	76	140	35	38	742	19	165	48	858
2014	401	19	7	4	22	455	40	74	180	46	38	780	29	157	58	832
2015	400	15	6	2	19	523	38	46	103	28	38	847	23	158	47	845
2016		30	11	6	19		38	41	121	32	38		22	178	52	

to simulate loads from each of those tributaries. While there are reports of SWAT's limitation in handling freeze/thaw cycles (Qi et al., 2016), our seasonal analyses for the calibrated model showed no particular bias for winter estimates because we used observed snow parameters during the calibration processes (ESM Table S1). Simulation results were reported for each of these major tributary watersheds, and neighbor watersheds with similar characteristics were assumed to respond similarly (e.g., the Black for the Belle and Pine; the Thames for the Essex).

The model was then used to test the watershed's sensitivity to seven practices. Reduced nutrient application rates (Rate), subsurface placement of nutrients (PL), controlled drainage, and cover crops (CC) practices were applied to all croplands. The wetlands (WT), filter strips (FS), and grassed waterways practices were applied to all lands, including permeable urban areas. Based on analysis of the individual practices and discussions with the advisory group, five bundles of practices were selected, and each bundle was evaluated under three adoption strategies: (1) applied to all appropriate land (2) applied randomly to 55% of the appropriate land, and (3) focused on the 55% of the land with high TP or DRP yields (Dagnew et al., 2019b). Here, and throughout this paper, "appropriate lands" are lands where a practice can be implemented. For example, cover crops, subsurface placement, and fertilizer reduction can only be implemented in croplands while wetlands can be implemented for any land use type. When applied in bundles: WT assumed that 1% of every subbasin's land area was

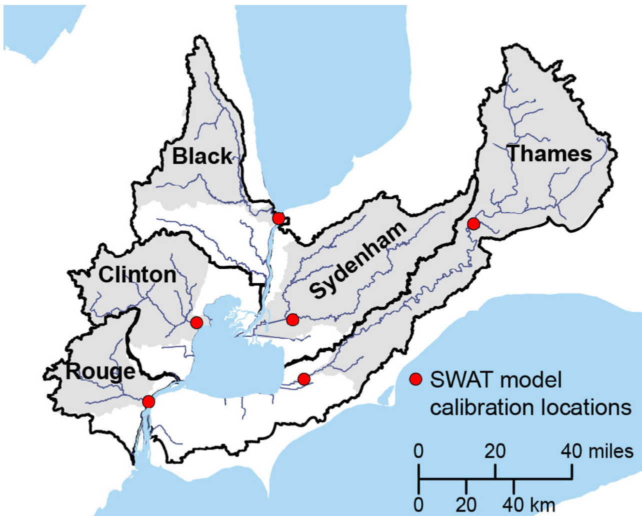

Fig. 3. SWAT model calibration locations. Areas shaded gray and labeled with bold text represent the calibrated river watersheds. Calibration and scenario results for those watersheds are assumed to be representative of adjacent areas (not shaded) within the bold black lines.

converted to a wetland and those wetlands were positioned such that 50% of the flow in a sub-basin passed through them; PL placed 80% of nutrients sub-surface and 20% on the surface; FS assumed 1.7% of a farm field was converted from crops to a filter strip/buffer strip, with other parameters set to simulate a medium quality FS; CC assumed cereal rye was planted in the fall on fields growing corn and soybeans; and Rate assumed a 25% reduction in N and P inputs to a farm field, including both inorganic fertilizers and manure.

Urban analysis

To examine the effects of green infrastructure across broad urban/suburban areas, Dagnew et al. (2019b) used SWAT to test the effects of increasing pervious area with and without additional vegetation in urban areas in the Clinton and Rouge watersheds (Fig. 1). To explore the potential for reducing combined sewer overflows (CSOs) in the GLWA WRRF sewer service area (Fig. 2), the calibrated Storm Water Management Model (SWMM) which included 402 subcatchments with unique land cover, soil, grey infrastructure, and connectivity (Hu et al., 2018) was used. The model was calibrated for volume at outfalls of 12 retention basis, two wet weather outfalls at the WRRF, and inflows to the WRRF. To identify subcatchments that contribute most to wet weather discharge at the WRRF as well as to the total system CSO volume, rainfall was eliminated for one subcatchment at a time, and the resulting percent reductions were calculated. This analysis is analogous to converting that catchment to a separate stormwater system. The model was also used to simulate implementing two forms of green infrastructure under average and extreme storms (Hu et al., 2019).

Results

New estimates for the Detroit River load

Phosphorus from Lake Huron dominates the Detroit River load

Burniston et al. (2018) noted that the TP concentrations entering Lake St. Clair were considerably higher than those leaving Lake Huron, especially for particulate phosphorus. Scavia et al. (2019a) found similar results, and showed that the difference was not caused by additional phosphorus from the St. Clair River watershed. They estimated that 54% of the Detroit River load originates in Lake Huron. Satellite imagery revealed frequent large sediment resuspension events along Lake Huron's southeastern shore that can persist for days and evade detection at the two monitoring stations. While sampling at the Point Edward station could detect such events, it was shown to be not frequent enough to catch many of them (Scavia et al., 2019a). This unmeasured load increased over the study period from 2001 to 2016, in concert with climate-driven declines in ice cover and increased frequency of large storms, approaching the sum of the measured loads from Lake Huron and the St. Clair River watershed (Fig. 4). Nicholls (1998) showed a strong correlation between 1976 and 1994 January-May TP concentrations at the Lake Huron outflow and maximum percent ice cover and lake level, with ice cover being the stronger driver. He suggested the increased TP concentration could also result from resuspended sediment from Saginaw Bay.

The bioavailability of this substantial previously unmeasured load from Lake Huron is unclear at this point. For example, Thomas and Haras (1978) found 40–80% of phosphorus from eroded shorelines was in the unavailable apatite inorganic P form. However, Howell et al. (2014) showed high concentrations of P in resuspended sediment likely derived from fluvial inputs and settled algae. Nicholls (1998) suggested the elevated P load could be resuspended and transported material from Saginaw Bay. Detailed measurements of the various P fractions sampled during the episodic fluxes are needed.

This updated estimate of the Lake Huron contribution does not impact the Scavia et al. (2019a) or Burniston et al. (2018) estimates of the Detroit River load because these are based on measurements at the outlet of Lake St. Clair and measurements in the Detroit River, respectively, effectively capturing the full Lake Huron contribution. However, as discussed below, this unmeasured load does impact our understanding of the relative importance of different nutrient sources and therefore the potential allocation of load reduction targets.

After Lake Huron, the largest phosphorus contributors are nonpoint sources, followed by the WRRF in Detroit and other point sources (Fig. 5a). Average annual TP loads from the US (798 MTA) are higher than those from Canada (601 MTA).

Lake St. Clair is a TP sink

On average between 2001 and 2015, Lake St. Clair retained 20% of its TP inputs annually (Scavia et al., 2019a), *albeit* with substantial inter-annual variability (Fig. 5b). While measurements of DRP are less reliable, it appears that its annual retention is much lower,

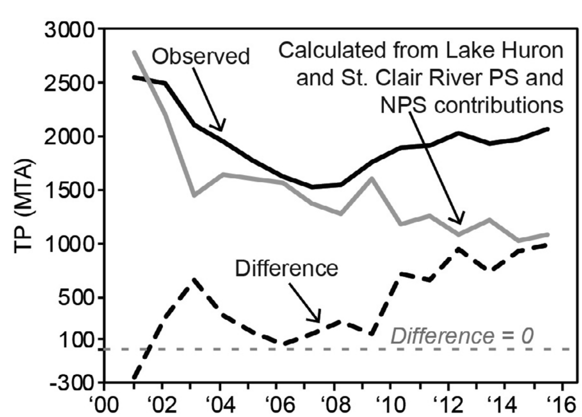

Fig. 4. TP inputs to Lake St. Clair measured at Algonac and Port Lambton (black line), and calculated from Lake Huron and the St. Clair River point and nonpoint source contributions (gray line). The difference (dashed line) represents the portion of the load that is entering Lake St. Clair but not accounted for in monitoring data.

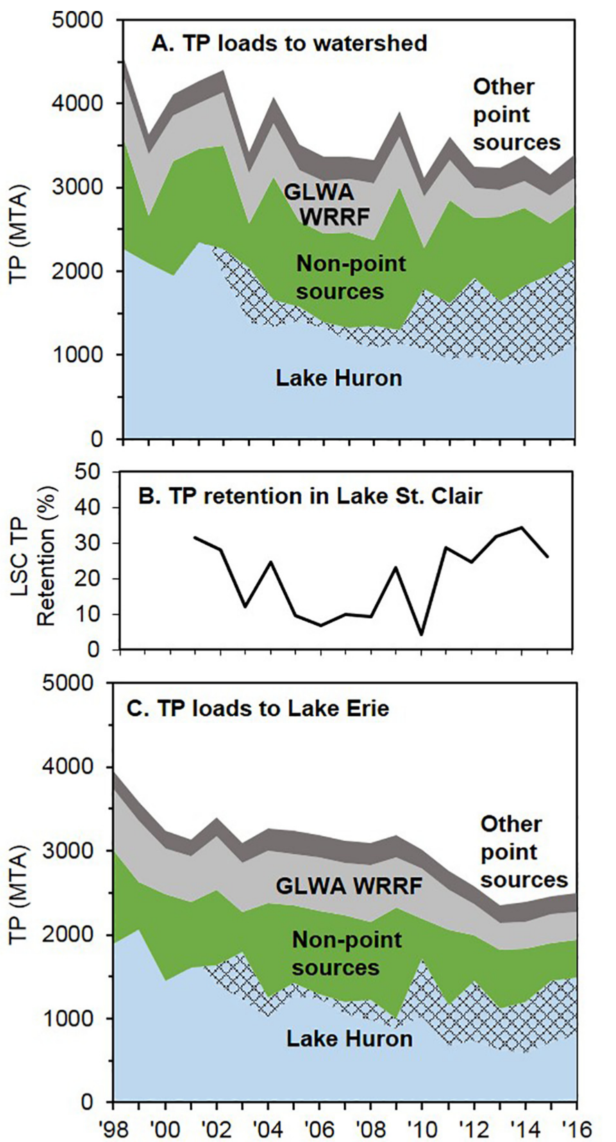

Fig. 5. A: Time series of the TP load components from the watershed (not accounting for Lake St. Clair retention). Hatched lines represent the unmeasured load from Lake Huron. B: Percent Lake St. Clair TP retention. C: TP loads to Lake Erie derived from the sum of the load from Lake St. Clair and other loads to the Detroit River.

perhaps approaching zero. Results from the ecological model (Bocaniov et al., in press), indicated that, for the simulation period 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 annual rate, likely because the model could only run for the ice-free season, and ice cover would increase retention via reduced mixing and elevated settling during times when ice-cover shields the lake surface from the wind stress. The model's high seasonal DRP retention is driven by rapid uptake by algae during the growing season. To the extent that the annual DRP retention rate is accurate, it suggests that in this shallow lake much of the DRP retained during the growing season is recycled back into the water and exported during the colder months.

Scavia et al. (2019a) suggested zebra and quagga mussels could have contributed to the sequestration of phosphorus into the bottom sediment of Lake St. Clair. 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, Bocaniova et al. (in press) showed that wave-induced bottom shear stress (the driver of sediment resuspension in shallow lakes) is not strong enough to resuspend sediments in the 30% of the lake with depths greater than 5 m. So, deposition of sediment in those areas is also a likely contributor to phosphorus retention. They also showed 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 the year-to-year variability in the annual retention estimates (Fig. 5b).

Revised Detroit River loads

As described above the new Lake Huron load estimate and Lake St. Clair retention estimates are important, but they do not affect the updated Detroit River TP load estimates because those are based on the load leaving Lake St. Clair. The new estimates (Scavia et al., 2019a) (Fig. 5c) are higher than those estimated by Maccoux et al. (2016) and lower for two of the three years estimated by Burniston et al. (2018). The variations among these estimates are likely because the Maccoux et al., used the earlier underestimates for the Lake Huron load, and Burniston et al., used LOADEST (Runkel, 2013), which may not be appropriate for connecting channels. The Detroit River load declined roughly 37% from 1998 to 2016 due to declines in Lake Huron phosphorus concentrations after the 2000–2005 invasion of zebra and quagga mussels, and significant improvements in WRRF operations around 2010. There was no statistically significant trend in other sources over this time period.

Options for reducing loads

Meeting a 40% reduction for the Detroit River

A 40% reduction from the updated 2008 Detroit River load estimate (3,096 MTA, Scavia et al., 2019a) results in a 1,858 MTA target. Our estimates indicate the Detroit River TP load has already declined to 2,425 MTA (based on an average for 2013–2016), so 567 MTA remains to be reduced (Fig. 6). This is equivalent to 23% of the phosphorus load coming from all sources, including Lake Huron. .

After Lake Huron, the largest sources of phosphorus are the WRRF, followed by the Thames River watershed, unmonitored loads to Lake St. Clair, and the Sydenham and Clinton river watersheds (Fig. 7). The remaining 10% comes from unmonitored load to the Detroit and St. Clair rivers, and the Black, Rouge, Belle, and Pine river watersheds.

Contributions and potential reduction of point sources

Point sources contribute 43% of the TP watershed load (that is, the load excluding the Lake Huron contribution) and 50% of the watershed DRP load. When considering point source contributions, roughly 83% of the TP load and 85% of the DRP point source loads come from the US (Fig. 8), representing 15% and 25% of the Detroit River's TP and DRP loads to Lake Erie.

Detroit's WRRF's TP load declined by 44.5% since 2009 (MDEQ, 2016; Hu et al., 2019), but still currently contributes 54% of the total point source TP and DRP load. However, while beyond the scope of this study, treatment processes and technologies will likely continue to improve, and it could be possible for some of these advances to be implemented in the future. While non-

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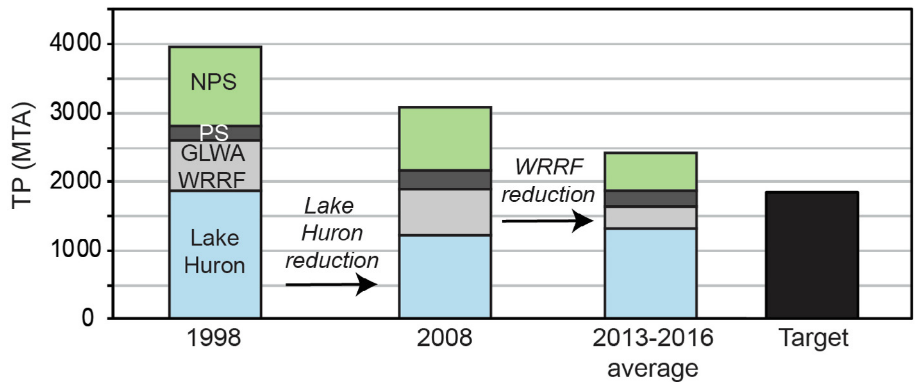

Fig. 6. Contributions from nonpoint sources (NPS), point sources (PS), the Great Lakes Water Authority WRRF, and Lake Huron to the Detroit River TP load to Lake Erie at several time periods, accounting for Lake St. Clair retention. The target represents a 40% reduction from the 2008 load.

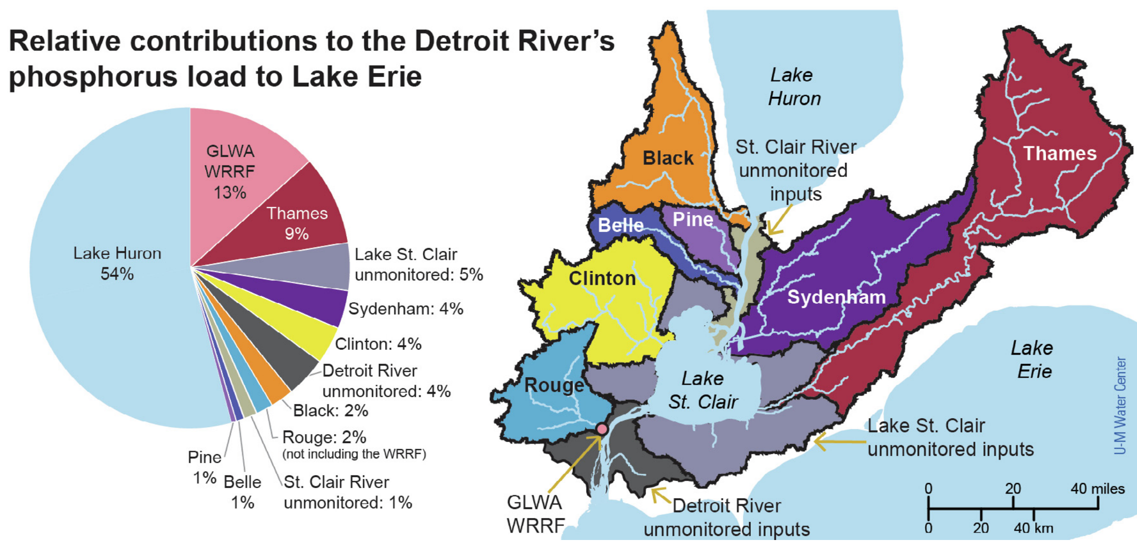

Fig. 7. Proportions of the Detroit River's TP load to Lake Erie from all sources. The Great Lakes Water Authority Water Resources Recovery Facility (GLWA WRRF) in Detroit is shown separately from the Rouge watershed in this case.

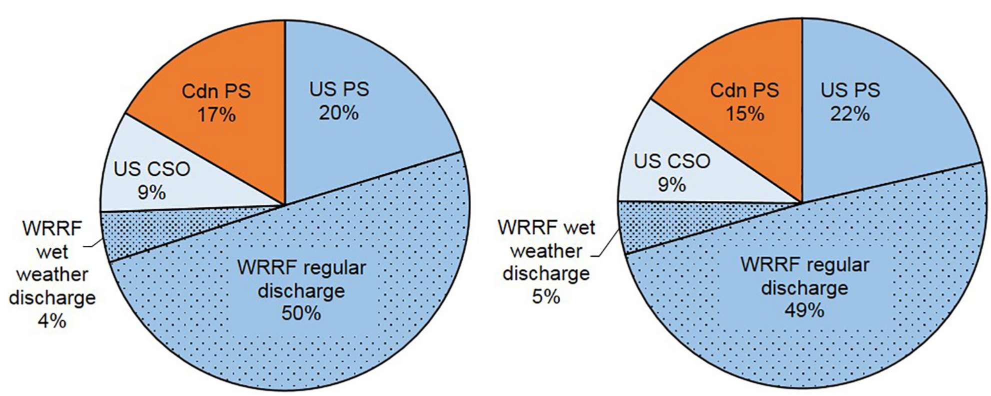

Fig. 8. Proportions of the watershed TP (left) and DRP (right) loads from US and Canadian point sources. The load from Lake Huron is not included here.

trivial in technological, human resource, and financial costs, improving treatment operations could potentially have one of the biggest impacts on reducing the watershed's phosphorus load. Treatment improvements at some of the other point source facilities could also be possible. Beyond that, the focus in urban areas turns to CSOs and runoff, and they each constitute only about 2% of the Detroit River's load to Lake Erie.

Because both CSOs and runoff are primarily driven by rainfall and the amount of impervious surface (Dagnew et al., 2019b, Hu et al., 2019), reducing phosphorus load from these sources would likely require increasing pervious areas. SWAT analyses (Dagnew et al., 2019b) for the Rouge and Clinton watersheds demonstrated that both TP and DRP loads are reduced as pervious surfaces increase, and that because of increased evapotranspiration, the reductions were roughly doubled if a transition from impervious to pervious cover included added vegetation. The SWMM analyses (Hu et al., 2019) suggested that within the WRRF sewer service area, green infrastructure such as bioretention cells and increasing pervious areas could work well for some upper reaches of the system, but more complex interventions are likely needed downstream.

Contribution and potential reduction of nonpoint sources

Nonpoint sources contribute 57% and 50% of the TP and DRP loads from the watershed, respectively. Dagnew et al. (2019b) estimated that 59% of the watershed's nonpoint source TP and 68% of the nonpoint source DRP come from Canadian agricultural lands, compared to 12% and 6% from US agricultural lands. Runoff from urban and suburban lands make up about 10% of the watershed's nonpoint source TP and DRP loads (Fig. 9).

Estimated loss of nonpoint source DRP and TP per hectare (loss yields) from agricultural lands showed that losses were generally higher in Canada than in the US, especially for DRP (Fig. 10). While this difference may be due to higher fertilizer application rates and more intense drain tile spacing in Ontario, running the SWAT model with the same fertilizer application rates and tile systems in both the US and Canada produced essentially the same patterns in loss yields. Thus, those differences are more likely driven by differences in precipitation and soil characteristics (ESM Fig. S1). Those characteristics in Canada are more similar to the Maumee River watershed, which delivers almost half of the phosphorus to the western basin. While the slopes in both the US and Canadian agricultural areas are similar to the Maumee, average annual precipitation in in the upper Sydenham and Thames is similar to that in the Maumee watershed and greater than that in the St. Clair and Detroit River watersheds. Similarly, the Canadian soils are largely poorly drained like those in the Maumee, whereas the US soils are well drained (ESM Fig. S4). Our estimates for the Canadian watersheds (0.78–1.38 kg/ha) are similar to those from edge of field analyses measured at the outlet of a very small (19.5 km^2) subbasin (Upper Medway watershed) within the Upper Thames watershed in 2002–2016 (0.25–5 kg/ha, averaging at 0.62 kg/h; WEG, 2018) and at three other sites in Canada (0.18–1.9 kg/ha for TP; Plach et al., 2019).

The highest single-practice TP and DRP load reductions were achieved with wetlands (WT), followed by filter strips (FS), subsurface placement of nutrients (PL), cover crops (CC), and reduced fertilizer application rates (Rate) (Dagnew et al., 2019b). The edge of field study for the Medway watershed (WEG, 2018) indicated that TP and DRP reduction by using wetlands, buffer strips, and grassed waterways vary among fields. As a result, even with the extreme case of 100% adoption, none of the practices implemented alone achieved a 40% load reduction at their sub-watersheds' outlets. Hence, the need for implementation of multiple practices seems inevitable. In our analysis, the bundle of practices that included filter strips, wetlands, and cover crops on 100% of the appropriate lands performed best, followed by one that included fertilizer subsurface placement, wetlands, and cover crops (Fig. 11). These bundles each reduced TP and DRP loads from the agriculturally-dominated Sydenham, Thames, and Black river watersheds by as much as 60–80%. Other combinations could potentially achieve at least a 40% reduction from those watersheds (Dagnew et al., 2019b).

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. Adding filter strips to the CC-PL bundle further decreased the TP and DRP loads from the Sydenham and Thames rivers, and it was particularly effective for reducing the TP load from the Black watershed.

Dagnew et al. (2019b) also showed that placing the practices on just the 55% of the land with the highest TP and DRP yields also surpassed target-level reductions. For example, a 55% focused implementation of CC-FL-WT could achieve a 50% load reduction in the Sydenham sub-watersheds for both TP and DRP (Fig. 11, upper right). The Thames River may require slightly more than 55% to reach the same reduction levels. It is important to note, however, that while the model demonstrates the benefits of focusing practices on high phosphorus loss lands, in practice those areas will have to be identified on the ground using farm- or field-level management information (e.g., Muenich et al., 2017).

The Thames River

The binational agreement also calls for a 40% reduction in spring (March-July) TP and DRP loads for, among other watersheds, the Thames River. So, we tested the impacts of key bundled scenarios on the Thames River spring load and the Sydenham and Black rivers for comparison. In testing the bundle most effective for annual TP reductions (CC-FS-WT), one that replaced cover crops with subsurface placement (PL-FS-WT), and one that tested reduced fertilizer application rates and subsurface placement (Rate-PL), Scavia et al (2019b) showed that in all cases, the spring load reductions equal or surpass the annual load reductions for

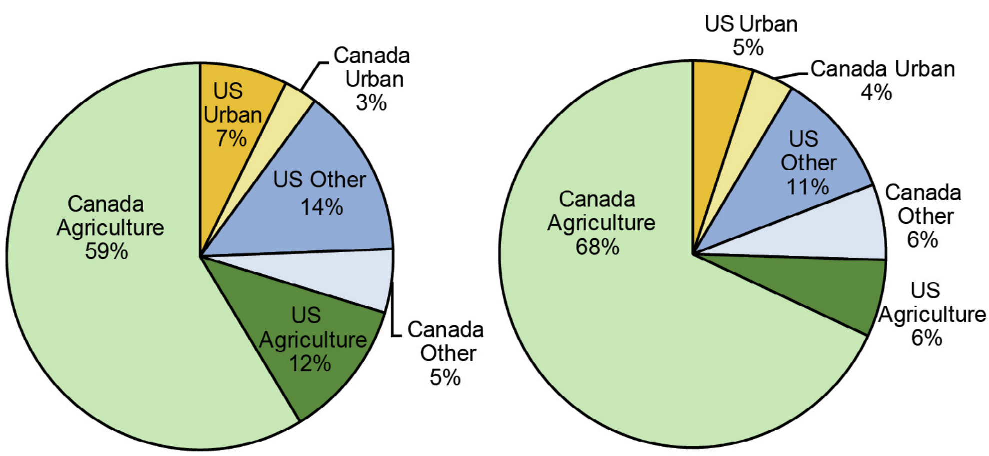

Fig. 9. Proportions of the watershed TP (left) and DRP (right) loads from US and Canadian nonpoint sources (NPS) coming from agricultural land (i.e., cropland and pastureland), urban land, and other land (i.e., forests and wetlands) derived from SWAT. The load from Lake Huron is not included here.

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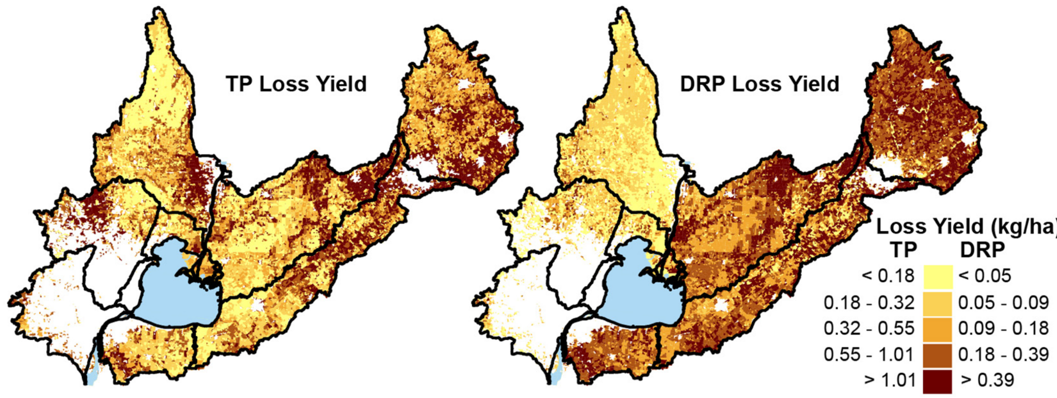

Fig. 10. Modeled TP and DRP loss yields (kg/ha) for each SWAT model unit (HRU). Data from urban areas (shown in white) are not included so comparisons can be made across agricultural lands only.

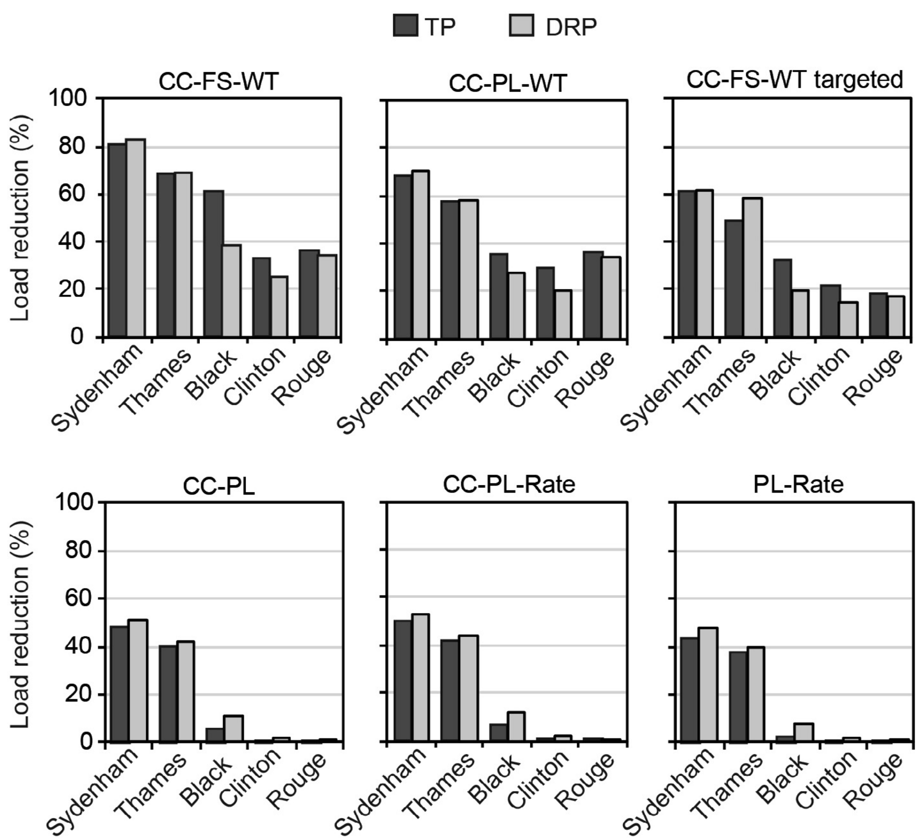

Fig. 11. Percent reductions of TP and DRP for bundled scenarios. Each bundle assumes 100% implementation, except the "targeted" scenario, which places practices on the 55% of land with the highest DRP and TP yields. For bundles that altered fertilizer rates, we assumed a 25% reduction in fertilizer application rates.

those sub-watersheds (Fig. 12). Thus, practices selected to address annual TP loads would also be effective for spring TP and DRP loads.

The Thames River is also of particular importance because changes in its load lead to more substantial changes in the load leaving Lake St. Clair (Bocaniov et al., in press). That load, along with re-suspended material, is transported along the shallower east and southeast shore toward the lake's outflow. In addition, its load is largest in late winter, early spring, and late fall when algal uptake is low and circulation favors shorter river water residence times (~11 days). In contrast, the Sydenham is located further from the lake outlet and separated from it by a basin deep enough (≥5 m) to support sediment accumulation. However, as Bocaniov et al. (in press) pointed out, because the load to Lake St. Clair is dominated by the St. Clair River, even a 50% decrease in any of its other tributaries would result in less than 5% decrease in the load leaving the lake.

Climate change will likely make reaching targets more difficult

Using the delta change method based on six downscaled climate model results for the Maumee River Watershed, Scavia et al. (2019b) used monthly average precipitation and temperature changes between the present (1996–2015) and mid-century (2046–2065) to assess the potential impacts of climate change. All but one climate model projected increases in annual precipita-

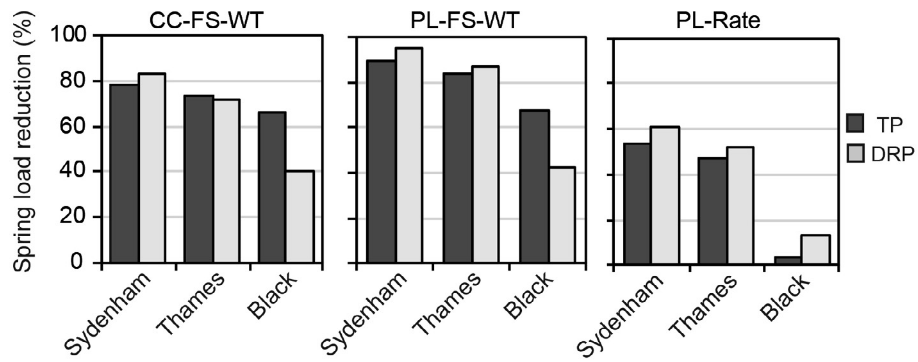

Fig. 12. Percent spring (March-July) TP (black) and DRP (gray) load reductions for three bundled scenarios. Each bundle assumes 100% implementation.

tion, and all models projected an increase in temperature. The 6-model average changes in annual precipitation and temperature were + 6.2% and + 2.7 °C, respectively.

Similar to other 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), increases in the timing and intensity of spring precipitation led to increased runoff and loads. Also similar to recent analysis for the Maumee watershed (Kalcic et al., 2019), increased temperature appears to mitigate some of the spring runoff because reduced snowpack reduces the intensity of spring runoff and increased evapotranspiration reduces the amount of water available to run off. Based on the output from the six climate models, SWAT projected that, on average, higher precipitation alone increased TP loads by 25% and DRP loads by 20%. Combining higher precipitation and temperature increased TP loads by 9.3% and DRP loads by 7.2%.

Discussion

In February 2016, the US and Canada called for a 40% reduction from 2008 levels in annual TP inputs to Lake Erie's western and central basins and spring TP and DRP from the Thames River watershed. The fact that 54% of the TP load to Lake Erie originates in Lake Huron, even though 20% of the load is retained by Lake St. Clair, is a reminder that the Great Lakes are an interconnected system, and that upstream nutrient sources are important to consider.

The current contribution to the Detroit River load from Lake Huron appears to be more than twice the load estimated from measurements, and that unmeasured contribution has been increasing due to climate change (Nicholls 1998, Scavia et al., 2019a). This unmeasured contribution appears to come from sediment re-suspended along Lake Huron's southeast shore, and future efforts 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, however, to at least improve 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).

Taking into consideration the potential difficulty in controlling the Lake Huron load illustrates the challenge of meeting a 40% load reduction from the Detroit River, even though that load already declined by almost 22% since 2008. A modest 23% reduction of all loads would be needed to achieve the remaining 567 MTA reduction required to meet the target; however, if reductions from Lake Huron are not included, then a 51% reduction would be required from watershed sources. If further reductions from the GLWA WRRF are also not included because it has already been reduced by over 40%, then a 72% load reduction would need to be achieved from the remaining sources – a daunting challenge. However, reducing the Lake Huron and GLWA WRRF loads each by 10–15%, leaves 40–50% to be reduced from watershed sources, which simulations indicate would be possible.

Because point sources contribute 43% of the watershed's TP and 50% of the DRP (not including the Lake Huron contribution), they are logical targets. The WRRF in Detroit contributes 54% of the TP and DRP point source load in this watershed; however, substantial load reductions have already been made from this facility, and the high costs of further technological improvement may therefore be difficult to justify at this time. There are about 150 other point sources in the watershed that together contribute 46% of TP and DRP point source load, so additional reductions at those facilities should help. Because CSOs and urban runoff contribute little to the overall load, reductions from them would contribute little. However, to address other public health and environmental concerns, CSO reduction is generally a good practice and could be achieved through a portfolio of complementary green and gray infrastructure strategies.

Nonpoint sources contribute the remaining 57% and 50% of the TP and DRP loads and, similar to results from Maumee River watershed assessments (Muenich et al., 2016, Kalcic et al., 2016; Scavia et al., 2017), bundling agricultural management practices appears to work better than implementing single practices. Combining practices, such as cover crops, filter strips, wetlands, and subsurface placement of fertilizer, resulted in TP reductions greater than 50%. Bundled scenarios designed to address the annual TP load reductions for the Detroit River were even more effective for reducing the spring TP and DRP loads for the Thames, Sydenham, and Black rivers. As in the Maumee analyses, focusing practices on land with the highest phosphorus losses resulted in reductions that approach levels achieved from applying them on all agricultural lands. This focused approach, coupled with the relative effectiveness of different combinations of practices, suggests flexibility, where practices can be combined and applied to match the needs and preferences of producers. However, the simulations suggest that even extensive conservation on those lands may not be enough if the strategy is to get a 72% reduction from those lands alone, especially because the future climate is projected to increase loads.

It is also important to recognize that increased air temperature favors longer periods of lake stratification leading 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 (driving lake thermal stratification) explained almost nine times as much interannual variability in hypoxic area compared to variation in phosphorus loading, and that deeper stratification caused by warmer, longer summers led to larger hypoxic areas. Bocaniov and Scavia (2016) also showed that inter-annual differences in weather significantly influenced the spatial extent, duration and severity of anoxia and hypoxia. To advance scientific progress and better inform management, the interactions between climate and land management, as well as between climate and the lake, must be better evaluated to assess future changes in both the watershed and Lake Erie.

Domestic action plans adaptive management

To understand and assess the relative sources of and potential actions to reduce loads to Lake Erie from the Detroit River required assembling large data sets from both the US and Canada; developing, calibrating, and validating diverse models at different time and space scales; 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 (Muenich et al., 2016, Kalcic et al., 2016; Scavia et al., 2017), provide tools that can be used to guide policies and practices as the countries work within the GLWQA adaptive management framework. As new information becomes available, that framework enables both adjustments to action plans and improvements in models and other assessment tools.

Each Domestic Action Plan emphasizes that the targets and approaches 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. Much of what has been compiled, analyzed, and assessed herein is new since the targets were set and the action plans developed. Therefore, we anticipate our results will be helpful in evaluating both the overall load reduction targets and their allocation.

Potential plan adaptations could include: 1) enhancing conservation to reach a 72% reduction from nonpoint sources, 2) designing programs to reduce the Lake Huron and WRRF loads each by 10–15% so that the nonpoint source load reduction is more within reach; 3) relax the expectation of a 40% load reduction from the Detroit River and make up the difference from other watersheds; or 4) relax the overall 40% load reduction target for the western and central basins and accept more hypoxia. Of course, combinations of the above could also be effective.

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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.2019.09.008.

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