Estimating Tributary Phosphorus Loads for Western Lake Ontario

Toronto and Region Conservation Authority

Prepared by Ecosystem and Climate Science

March 29, 2024

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SUMMARY

Total phosphorus loadings to Lake Ontario have not been assessed since 2008 (Makarewicz et al., 2012). While a number of intensive studies are currently working to assess updated loads to Lake Ontario, results are not currently available. This report contains a preliminary examination of sites along Western Lake Ontario and assesses current data availability from routine monitoring programs with the goal of providing total phosphorus estimates to the lake. Since more detailed projects are underway, the purpose of this work is not to duplicate efforts, but to provide a baseline to compare the more intensive efforts with. Results can be used to identify differences in the magnitude of loading estimates acquired through routine monitoring programs versus the more intensive storm event sampling currently underway.

Discharge and water quality stations across Western Lake Ontario, from Niagara to Cobourg were assessed to determine which watersheds contained current data records for the purpose of calculating total phosphorus loadings to Western Lake Ontario. Data was acquired through provincial and federal open data sources, in addition to data sharing agreements with Conservation Authorities. Discharge records often lacked continuous records, and provisional data were used where necessary. Water quality samples were not consistently measured across all seasons in space or over time, however, winter samples were available for most of the sites chosen for analysis.

Digital elevation models were used to delineate watersheds, discharge station and water quality station drainage areas. Annual and seasonal (March through July) total phosphorus loads were calculated using Weighted Regressions on Time, Discharge, and Season with a Kalman filter (WRTDS-K) in 32 tributaries entering Western Lake Ontario. In 2022, annual loads ranged from 0.1 to 41.5 mT at stations with available data, and on average, 40% of the load was delivered between March 1st and July 31st. Bias statistics were variable ranging from -0.174 to 0.264, although approximately half are within +/- 0.1 (or +/- 10%). Excluding the Welland Canal, in general between 2108 and 2022, the largest contributors of the watersheds analyzed were, Twenty Mile Creek, Humber River, Don River, Duffins Creek, Oakville (Sixteen Mile Creek), Rouge River, and Credit River; these are in no particular order. It is evident that the Welland Canal is a complicated system. A more in depth understanding of the sample locations and flow directions and diversions would be required to assess whether this method is appropriate to calculate loads and have confidence in the resulting measurements.

Probability of exceedance curves show that the high flow events are not captured well, therefore, it is highly likely that loads generated using WRTDS-K using grab samples are under-estimating actual loads. In addition, lack of consistent storm event-based samples, and potentially changes in lab methods may also impact results.

Since there are a number of more intensive efforts underway (e.g. MECP event-based loading, University of Waterloo Machine Learning studies, watershed models) future comparison between these studies could provide an understanding of whether the data collected as a part of current water quality programs is sufficient in the priority watersheds, and to what degree additional high discharge events can provide greater accuracy. In addition, assessments could be made to ensure that EMC method results are transferrable to neighbouring watersheds.

BACKGROUND

Environment and Climate Change Canada (ECCC) (now Canada Water Agency, CWA) coordinates binational and domestic actions to manage phosphorus concentrations and loadings, in Lake Ontario and other Great Lakes. Recent assessments have highlighted that there are no current lake wide estimates of phosphorus loading to Lake Ontario and that Canada and US tributary monitoring programs are currently not coordinated at the level required to produce a binational total load estimate or track changes at a lake wide scale over time.

The most recent whole-lake estimates of phosphorus loads to Lake Ontario were published more than 10 years ago (Makarewicz et al., 2012) and there is the need to advance efforts that will contribute to updating estimates to the lake. In 2022, ECCC (now CWA) commissioned a study to inventory water quality and quantity monitoring programs to understand the extent of available data that could be used to support estimating phosphorus loads. This work suggested several areas along western Lake Ontario have suitable information to produce unbiased loading estimates, mainly due to the storm event water quality sampling program underway (and/or historical event based data). The objective of this work is to compile existing datasets, and calculate loading estimates for a minimum of 18 previously identified watersheds within Western Lake Ontario, while not duplicating the intensive event loading studies currently underway.

METHODS

Watershed delineations

Catchments draining to each stream water quality and flow station were delineated using ArcGIS (ESRI Inc. 2019). To generate flow accumulation and flow direction grids, we used a provincial Digital Elevation Model (DEM) (2015) at a 20-m resolution in Southern Ontario (OMNRF, 2019b) and a 5-km buffer of the study extent from quaternary watersheds (OMNRF, 2020). Pour points (i.e., drainage points) representing the monitoring station were created and manually aligned with flow lines from the flow accumulation grids. Catchments delineated using the flow accumulation grids were compared to a watercourse layer (ECCC, 2023) and subwatersheds (where available) by conservation authorities to ensure overlapping boundaries (Table 1).

Table 1: List of sources for subwatershed boundary references.

Source	Layer
Central Lake Ontario Conservation Authority (2024)	CLOCA Scientific Subwatersheds
Toronto and Region Conservation Authority (2019)	Subwatersheds TRCA
Credit Valley Conservation (2022)	Subwatersheds (2018)
Conservation Halton (2022)	Subwatersheds
Hamilton Conservation Authority (2023)	Subwatersheds and watersheds in the Hamilton Conservation Authority area
Niagara Peninsula Conservation Authority (2023)	Subwatersheds Area 2K NPCA

Finer corrections of the catchments were based on province-wide Light Detection and Ranging (LiDAR) data (10 cm) (OMNRF, 2019a) to produce further DEM models when stations did not align correctly to flow lines or modelled catchments crossed adjacent stream segments. Catchment areas that were not overlapping with the current watercourse were mostly due to underground stream segments and thus not captured by the DEM. These discrepancies were corrected with subwatershed data (e.g. NPCA, 2023) to align the boundaries.

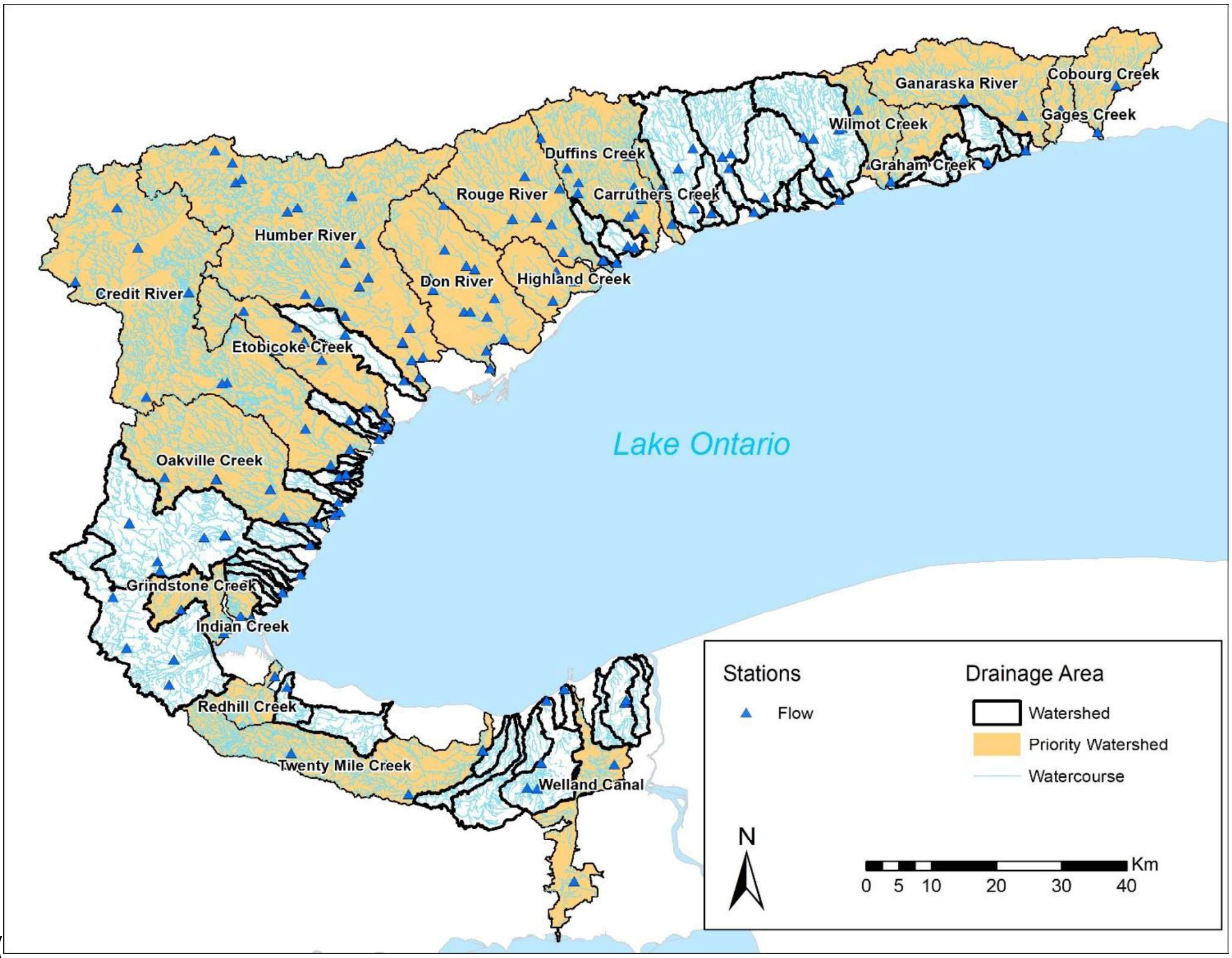
Using these water quality and flow stations drainage areas, additional drainage areas were derived for the upstream contribution to confluence pour points in a watershed where there was unaccounted input to these stations. Lastly, the watershed drainage area was defined using pour points at the mouth guided by the shoreline (ECCC, 2023). We ensured that the watershed boundaries aligned to the final drainage areas of water quality and flow stations, and confluence drainage areas.

The Welland Canal is a highly engineered system and modified landscape. As a result, the watershed and drainage areas of the water quality and flow stations were estimated using the subwatershed boundaries derived from Niagara Peninsula Conservation Authority (2023). Associated subwatersheds of the Welland Canal were adjacent to the canal and all upstream segments flowing into Lake Ontario. These subwatersheds were combined to define the final delineated watershed boundary of the Welland Canal.

Watershed landcover was classified using a national dataset as natural, rural, or urban area (NRCan, 2020). The 2020 dataset is a 30-m resolution of landcover derived using observation from Operational Land Imager (OLI) Landsat sensor. The raw data contains a single urban class, an agricultural class, and an open cover class that is categorized as rural in this study, and the remaining classes are natural cover.

Discharge

Discharge station locations were amalgamated from Water Survey of Canada (WSC) and Conservation Authorities across Western Lake Ontario



(Figure 1). While instances of municipal gauges were uncovered, they were in collaboration with Conservation Authorities with rating curves in preparation. Similarly, there are a number of stations within Conservation Authorities where rating curves are in preparation or nearly established (e.g. Central Lake Ontario Conservation Authority, Conservation Halton;

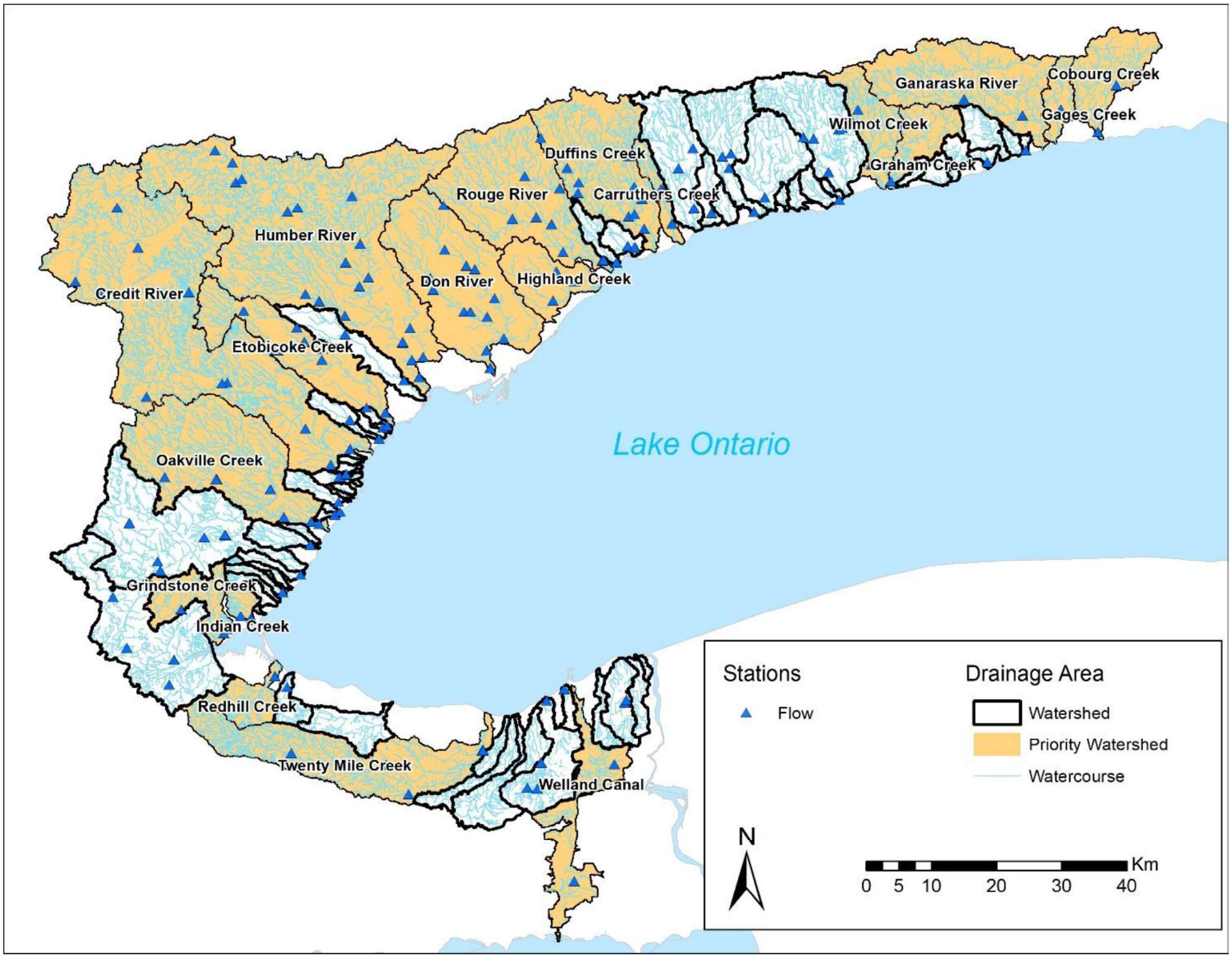


Figure 1: A map illustrating flow stations identified in Western Lake Ontario.

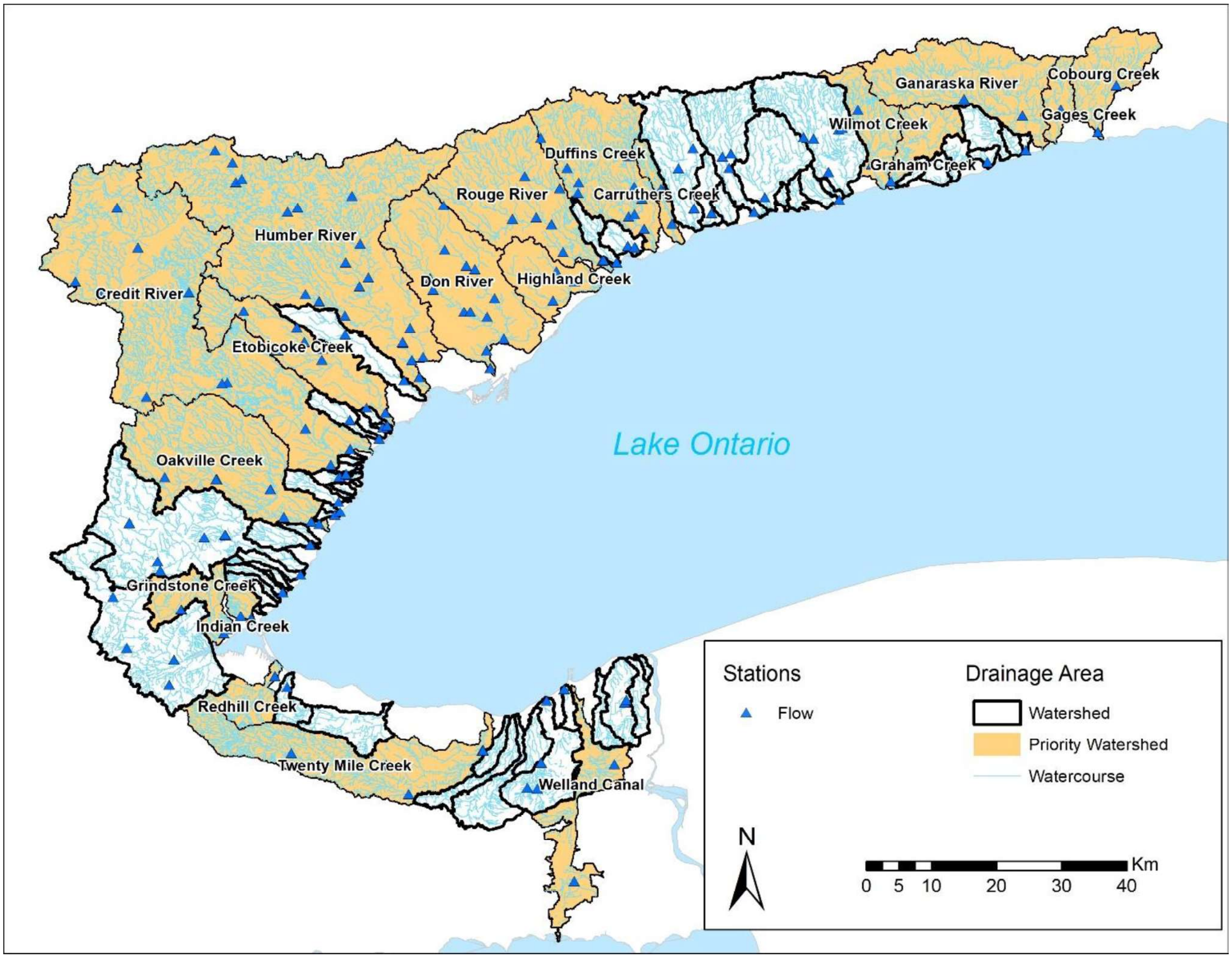


Figure 1, Appendix A:i Summary of stations). It is anticipated that within the next year, discharge will be available at the Conservation Halton stations with records extending back approximately 5 years. Additional sites will also be available within the jurisdiction of Central Lake Ontario Conservation Authority in upcoming years. A number of other Conservation Authorities also measure water level, however, it is unknown whether there are future plans to acquire stage-discharge relationships. In cases where multiple discharge stations were present from within the watershed, the WSC gauge was used in the analyses as it generally contained the longest data record. However, in upcoming years, some of the Conservation Authorities will have operational flow stations with rating curves closer to the mouths of the tributaries at a number of sites.

There are a number of tributaries where historical discharge data exists across Western Lake Ontario, however, sampling has ceased for unknown reasons. In some cases, the stream channel changes are too frequent making it difficult to maintain an accurate rating curve. For example, due to significant challenges rating Cooksville Creek there is a limited data record. Similarly, Water Survey of Canada historically measured discharge at Stoney Creek, however, monitoring ceased in 2014. Hamilton Conservation began sampling the Stoney Creek WSC Gauge in 2014. While flow has been measured, Hamilton Conservation Authority deemed the data unreliable. Due to the flashy nature of the creek and stoney bed, the creek profile is constantly changing and a reliable rating curve is not possible. While a data record exists for both water quality and discharge, we have omitted this station from our analysis. Water survey of Canada has also stopped measuring discharge at Harmony and Lynde Creeks.

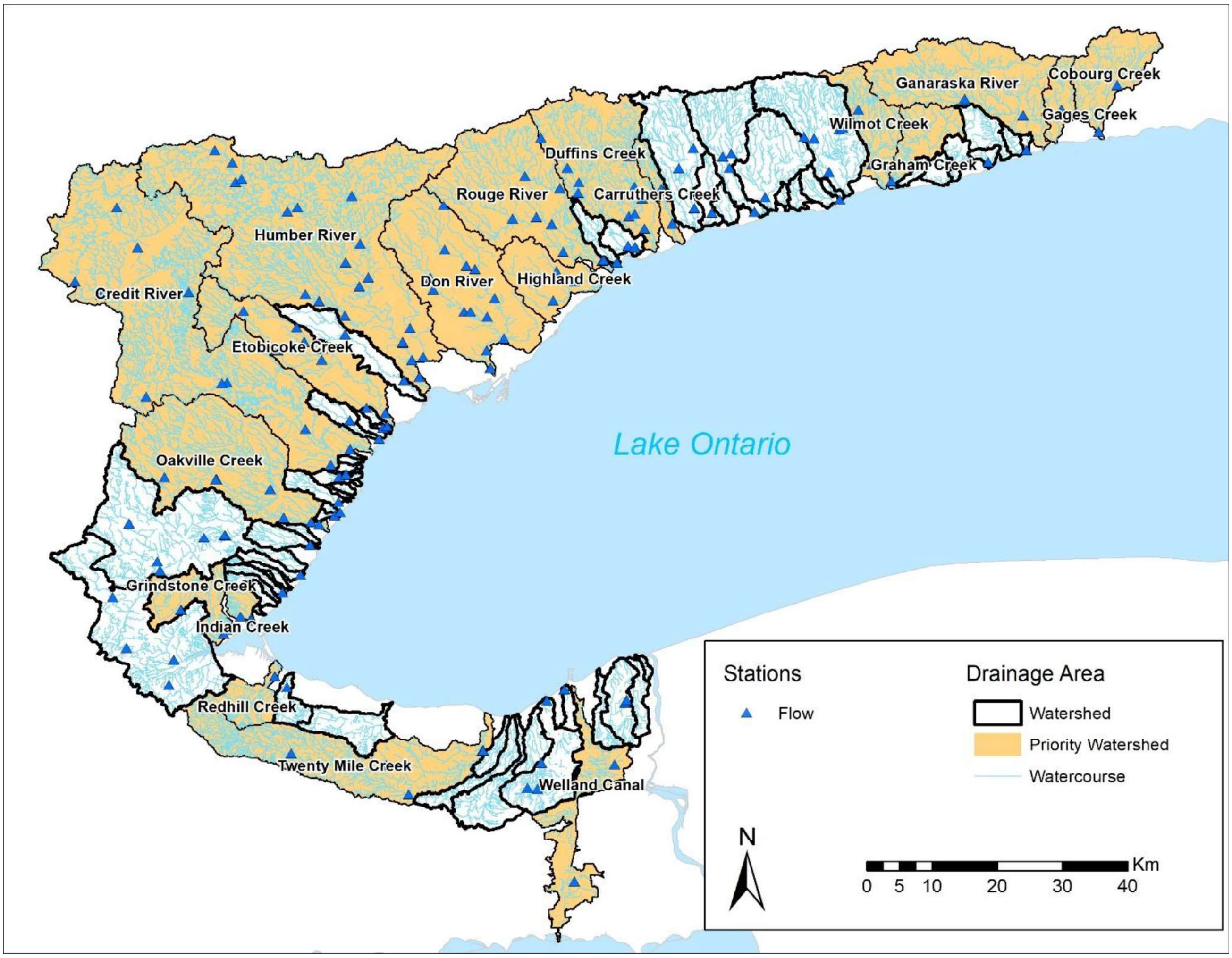
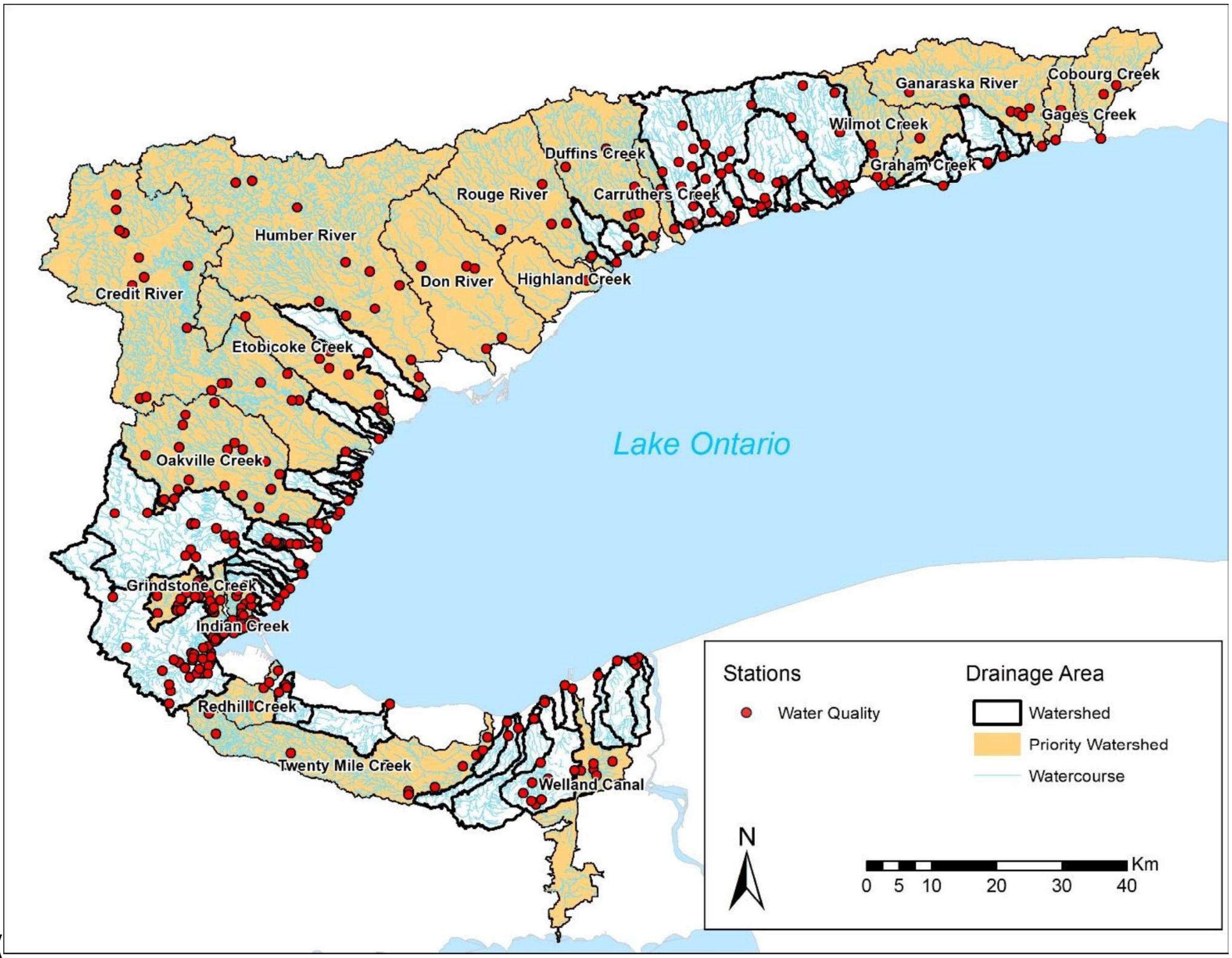


Figure 1: A map illustrating flow stations identified in Western Lake Ontario.

Water quality

Water quality stations within the Provincial Water Quality Monitoring Network (PWQMN), and Conservation Authorities (who send samples to commercial labs) were assessed across Western Lake Ontario



(Figure 2). Sites closest to the watershed outlets were selected to include in loading analyses. If Conservation Authorities augmented PWQMN sampling, datasets were merged. In the Hamilton area, Hamilton Conservation Authority also augmented their datasets using water quality from the Royal Botanical Gardens (e.g. at CP-7), however, this data was not acquired.

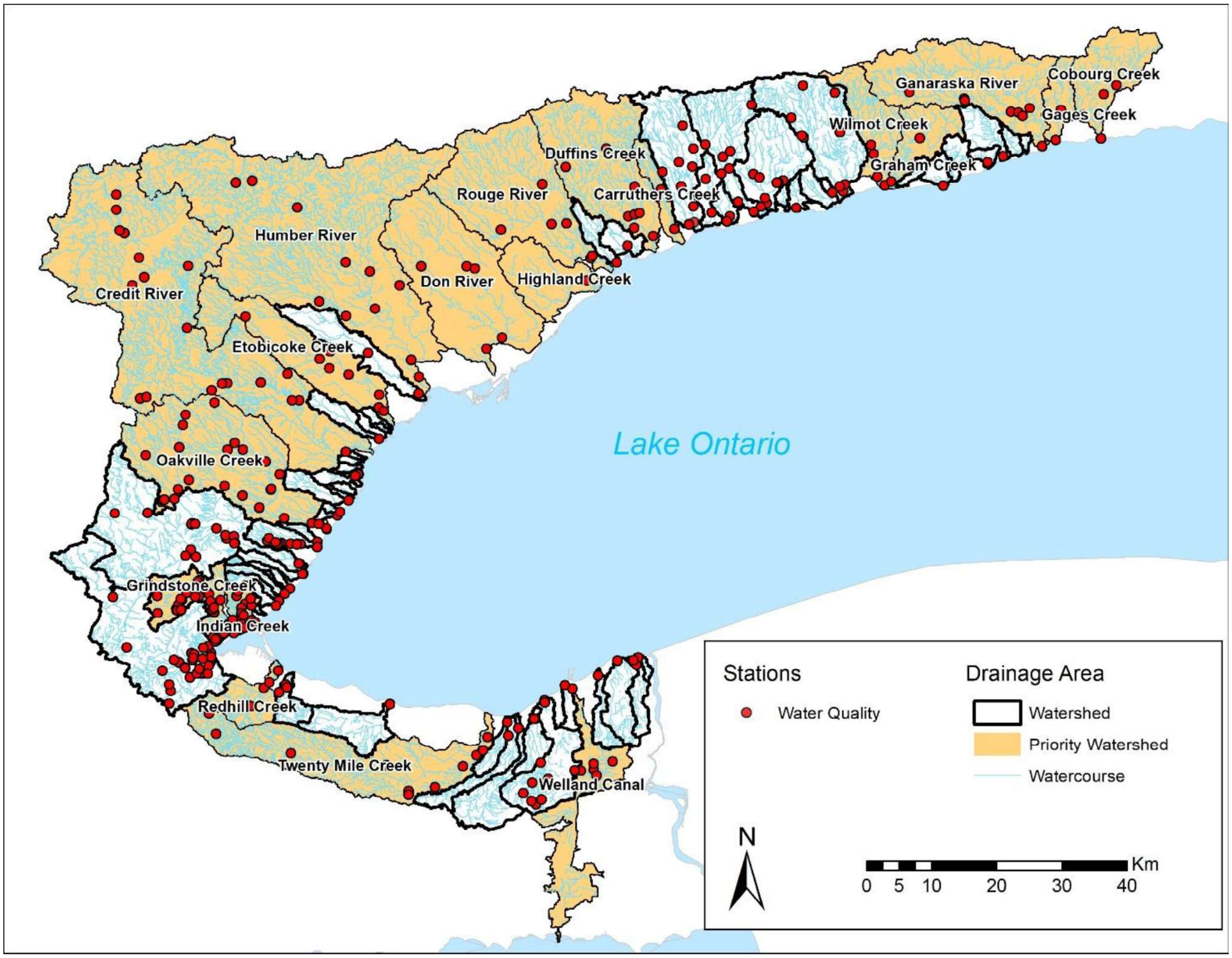


Figure 2: A map illustrating water quality stations identified in Western Lake Ontario.

PWQMN data were downloaded from the MECP's open data portal (February 29, 2024; https://data.ontario.ca/dataset/provincial-stream-water-quality-monitoring-network). Data were downloaded by time range then merged into a single data file. Only total phosphorus data were merged due to the large amount of data related to other parameters. Units were standardized to mg/L. Any records with units "mg/g dry" were deleted. Remark codes were evaluated for each sample and removed, retained, or investigated further data based on decisions outlined in Table 2. On days with multiple results, the data were averaged if results were similar. If the difference between duplicate samples were large, the data was omitted from analysis with no way to timely assess the reasons for the differences.

Table 2: Decision tree used for remark code evaluation. Note remark codes were merged from 3 separate columns in the PWQMN dataset.

Remark Code (from 3 separate columns)	Meaning	Number of samples	Decision
<MDL	LESS THAN METHOD DETECTION LIMIT	6	<
<W	NO MEASURABLE RESPONSE (ZERO): <REPORTED VALUE	13	<
< T	A MEASURABLE TRACE AMOUNT	19	keep
<TE	MEASURABLE TRACE AFTER EXTRA DILN/CONC:CAUTION	5	investigate further
<= W	NO MEASURABLE RESPONSE (ZERO):< REPORTED VALUE	1	<
<=W	NO MEASURABLE RESPONSE (ZERO):< REPORTED VALUE	4	<
<T	A MEASURABLE TRACE AMOUNT	65	keep
AIN	APPROX.RESULT: INTERFERENCE SUSPECTED	20	remove
RDB	CALCULATED VIA DIGESTED BLANK FROM ANOTHER RUN	42	keep
RDS	RESULT OBTAINED ON DILUTED SAMPLE	108	keep
RRV	RESULT VERIFIED BY REPEAT ANALYSIS	6	keep
SBO	SAMPLE BOTTLE OVERFILLED	10	keep
UAL	UNRELIABLE: SAMPLE AGE EXCEEDED NORMAL LIMIT	40	investigate further
>	ACTUAL RESULT > THAN REPORTED VALUE	3	remove

In November 2012, the MOECC Laboratory Services Branch adopted a new method for TP analysis, method E3516. Clients began raising concerns that method E3516 was providing lower results for TP than expected and clients, including PWQMN partners, began questioning the impact of the laboratory method change on TP results. In 2015, an inter-comparison study was conducted to test for equivalence between the two methods. Between March and September 2015, 800 samples were collected and analyzed by both methods. In April 2016, a memo was circulated to clients with a summary statement from the inter-comparison study. Method 3516 underestimated TP concentration; however, MECP recommended that users continue to use 3516 and site corrections would need to be made on a site-by-site basis. No site corrections have been made in the current datasets. We used method 3516 between August 2015 and December 2016, 3516 between January and May 2017, and method 3558 June 2017 and post. For stations 11000100502 on October 23, 2017 and station 6000300102 on November 27, 2017 only methods 3516 and 3036 were used. In these cases, we kept the TP value measured using method 3516.

Samples with UAL (unreliable – sample age exceeded normal limits) remark codes were included in the analyses. Although these samples “exceeded” the analytical holding time, major differences in total phosphorus measurements due to leaching were unlikely within the time frame until analysis. In addition, there was not a large quantity of samples with this remark code, concentrations fell within expected ranges, and the data are not likely to skew data results.

There were a number of TP concentrations that were extremely high (e.g. >1000 mg/L). We omitted these extreme data points from analysis as there is no way to ascertain their reliability within the current timeframe. However, there were also a number of datapoints that ranged from 1-5 mg/L. These data were included in the analyses. Future work could examine these data in the context of flow, precipitation, soluble reactive phosphorus, and total suspended solids to assess their validity.

Probability of exceedance

The probability of discharge exceedance was calculated for each watershed where loadings were being assessed. Discharge was ordered from largest to smallest and the probability that each unique discharge occurs was calculated. Sample presence over these discharges were then evaluated to assess the representativeness of the sampling regime across the flow conditions.

Loading estimates

Discharge was prorated to water quality stations using drainage areas. Discharge and total phosphorus concentrations at the water quality stations were used to calculate loading estimates in the R environment using Weighted Regressions on Time, Discharge, and Season with a Kalman filter (WRTDS-K) in the EGRET package. This technique uses flexible time varying relationships using concentrations, time, and discharge with unique weighted regressions for each day of the period of record being used. The Kalman filter treats the residuals on the day of sampling differently and uses the exact measurement on the day of sampling. Note this method is intended to provide the best export measurement on any given day. The method is not intended for use in evaluating watershed trends, however, the flow-normalized flux (which essentially removes the variability due to climate from the load) within the output can be used for this purpose. Loading results were prorated to the watershed outlets using watershed drainage areas. Annual loading estimates are presented for water years (e.g. 2022 water year = Loads between October 2021 and September 2022) in metric tonnes (mT). These data were the cumulative sum of daily loads, and will be underestimated at sites in years where flow records are not continuous. Bias statistics are reported for each watershed. A value close to zero suggests that the WRTDS-K model is nearly unbiased. Positive and negative values suggest positive and negative biases, respectively. Bias statistics between -0.1 and +0.1 indicate that the bias in estimates of the long-term mean flux is likely to be less than 10 percent.

Analyses required comparable data lengths for discharge and water quality records. In cases where records were longer for one parameter, data were removed from the longer data record. Additionally, in many instances, gaps in discharge data required the omission of water quality samples collected during the time frame of missing data.

Many tributaries contain branches which connect to the main channel and these branches appear to be a significant portion of the drainage area. In a number of watersheds (e.g. Spencer Creek, Rouge River, Cobourg Creek), discharge (and at times water quality) data were present above the confluence on both the main tributary channel and the branch. For Spencer and Cobourg Creeks, discharge was prorated to the confluence and combined prior to prorating to the downstream water quality station. However, for Rouge River, loads were calculated on the individual branches and combined. In some tables, the Little Rouge and Main Rouge branches are included separately, however, they have been joined for the loading estimate.

Seasonality

The seasonality of phosphorus delivery to Western Lake Ontario was assessed by calculating the percentage (%) of load exiting the watersheds in meteorological spring (March, April, May), summer (June, July, August), fall

(September, October, November), and winter (December, January, February). Note in these calculations, winter extends over two years (e.g. Winter 2022 = December 2021 + January 2022 + February 2022).

In addition, the cumulative loading between March and July (spring and part of summer) were also calculated in metric tonnes (mT) for each watershed.

RESULTS AND DISCUSSION

Delineated drainage areas for each of the watersheds in Western Lake Ontario are illustrated in Figure 3. Drainage aeras were also created for each flow and water quality station used in the loading analyses. The area associated with the Welland Canal is only the adjacent lands to the canal and does not account for the drainage area associated with Lake Erie. Excluding the Welland Canal, watershed areas ranged from 1.4 to approximately 900 km^2, with an average area of 92 km^2 (Figure 4). The majority of watersheds are small with a median area of 23.6 km^2.

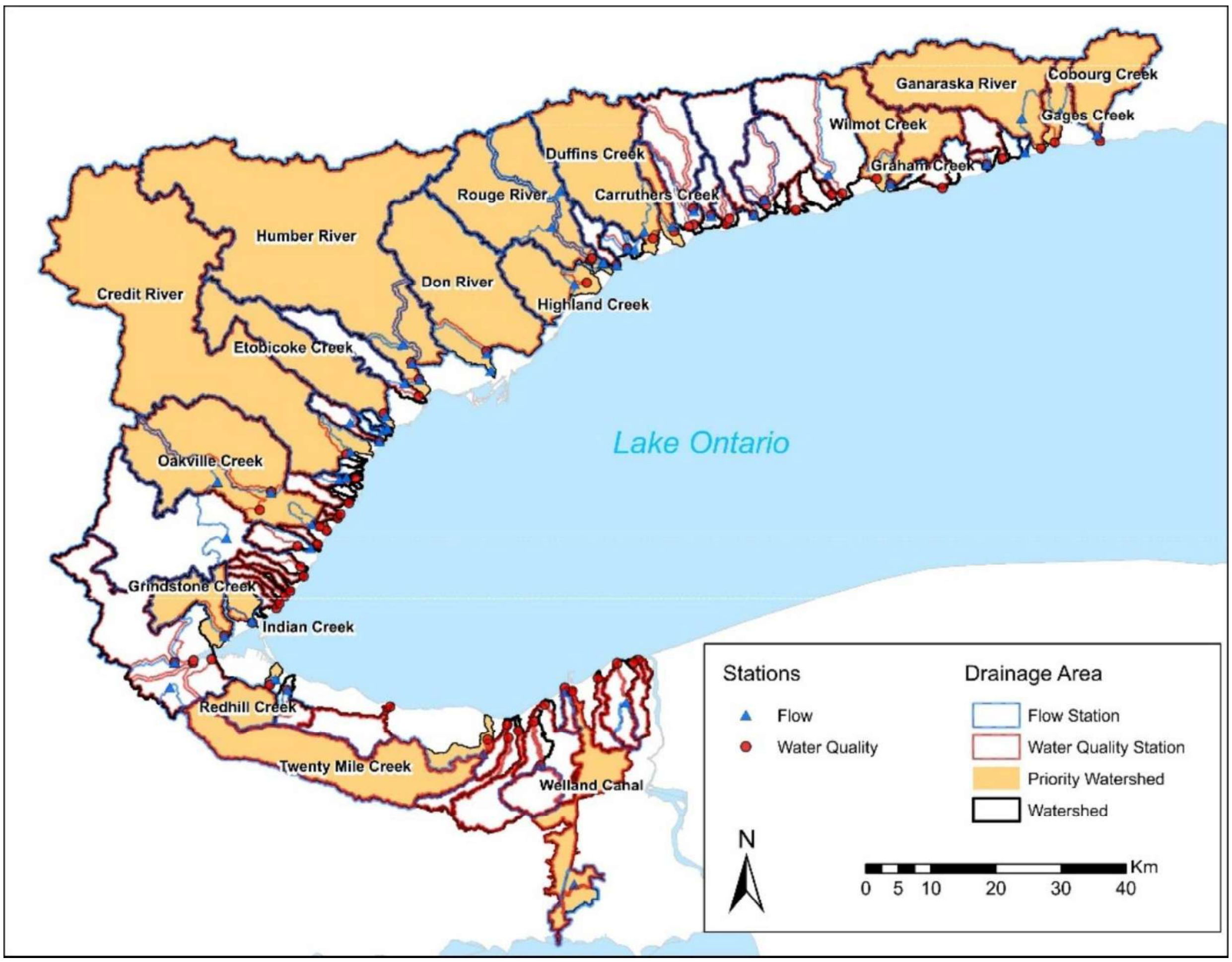


Figure 3: Delineated watersheds across Western Lake Ontario. Priority watersheds are highlighted in orange. Delineations for water quality and flow stations are also shown in red and blue, respectively.

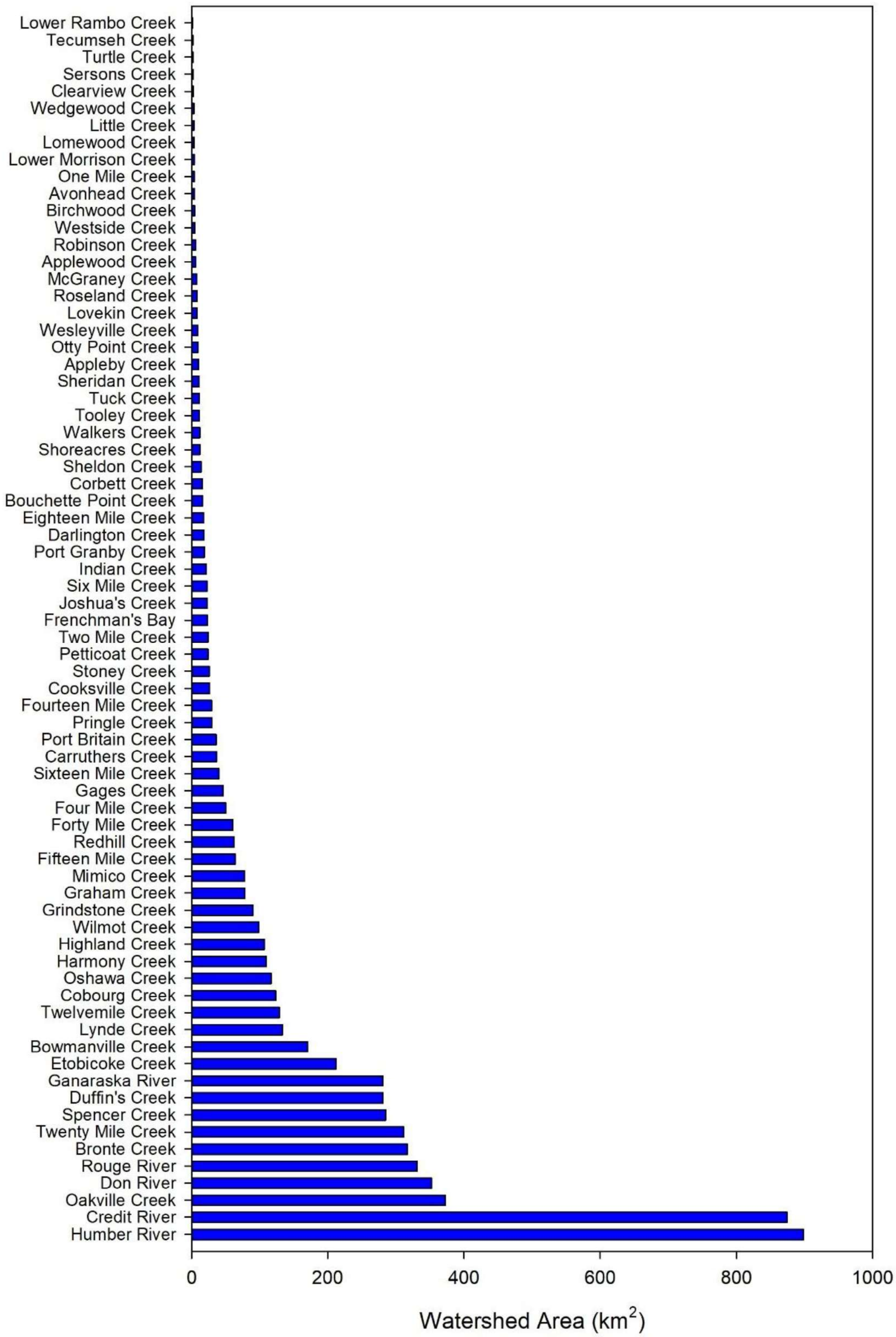


Figure 4: Watershed drainage areas across Western Lake Ontario in order of size, excluding the Welland Canal.

Land use adjacent to Western Lake Ontario is variable (Figure 5), ranging from 2-47% natural, 0.2 to 80% rural, and 7-98% urban (Figure 6). However, land use is predominantly urban in approximately half the watersheds, particularly in smaller watersheds closer to the lake (Figure 5, Figure 7Figure 6). Land use becomes important in terms of understanding loading results, particularly in terms of nutrient delivery in years with different weather patterns. For example, the export of phosphorus is often associated with agriculture sources (e.g., Michalak et al., 2013). However, work from mixed land use watersheds show that the variability in total phosphorus is a result of the differing importance between urban versus agricultural lands as they relate to climate with urban influences relatively more important in contributing TP during dry years (e.g., Tasdighi et al., 2017).

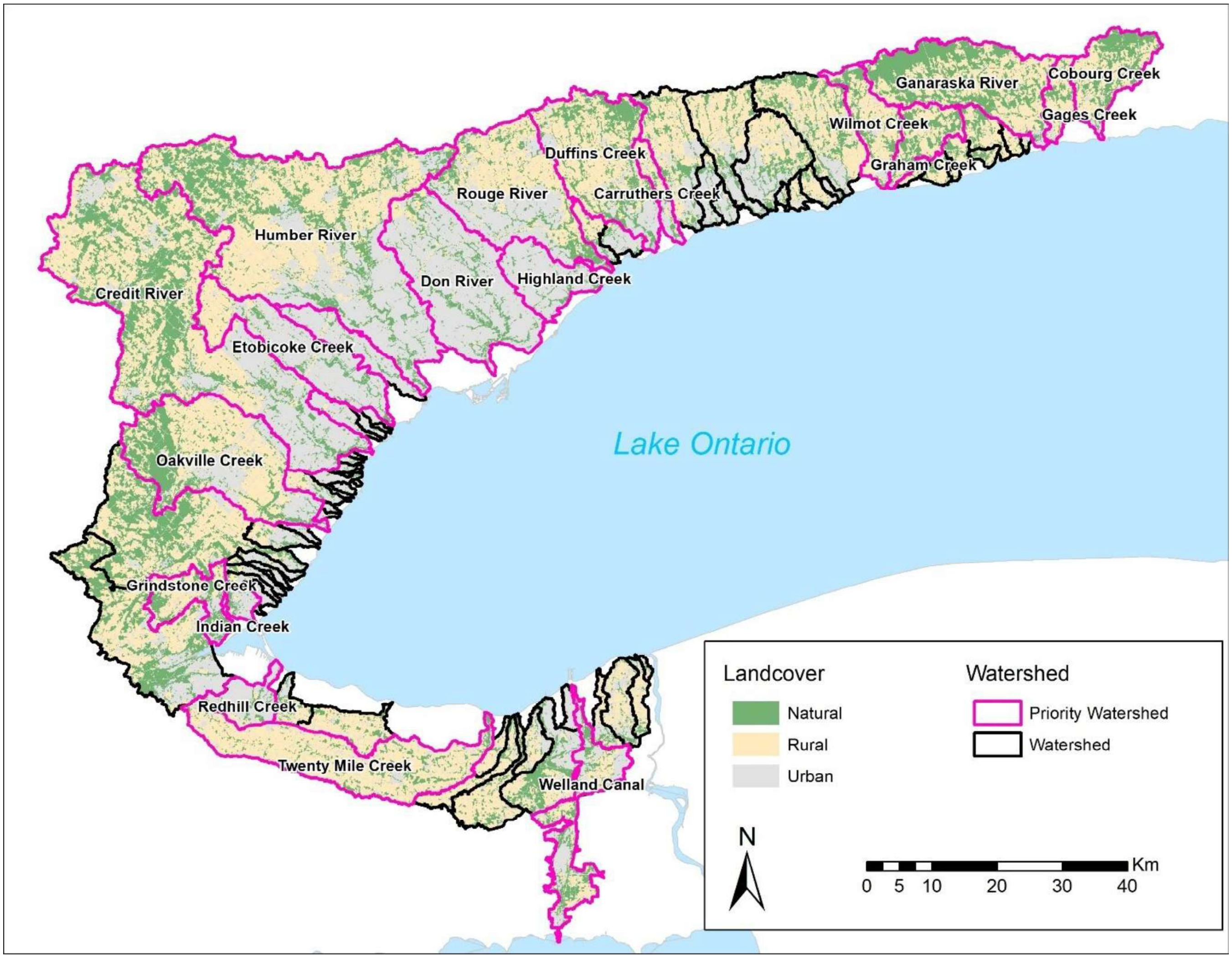


Figure 5: Land cover of watersheds adjacent to Western Lake Ontario.

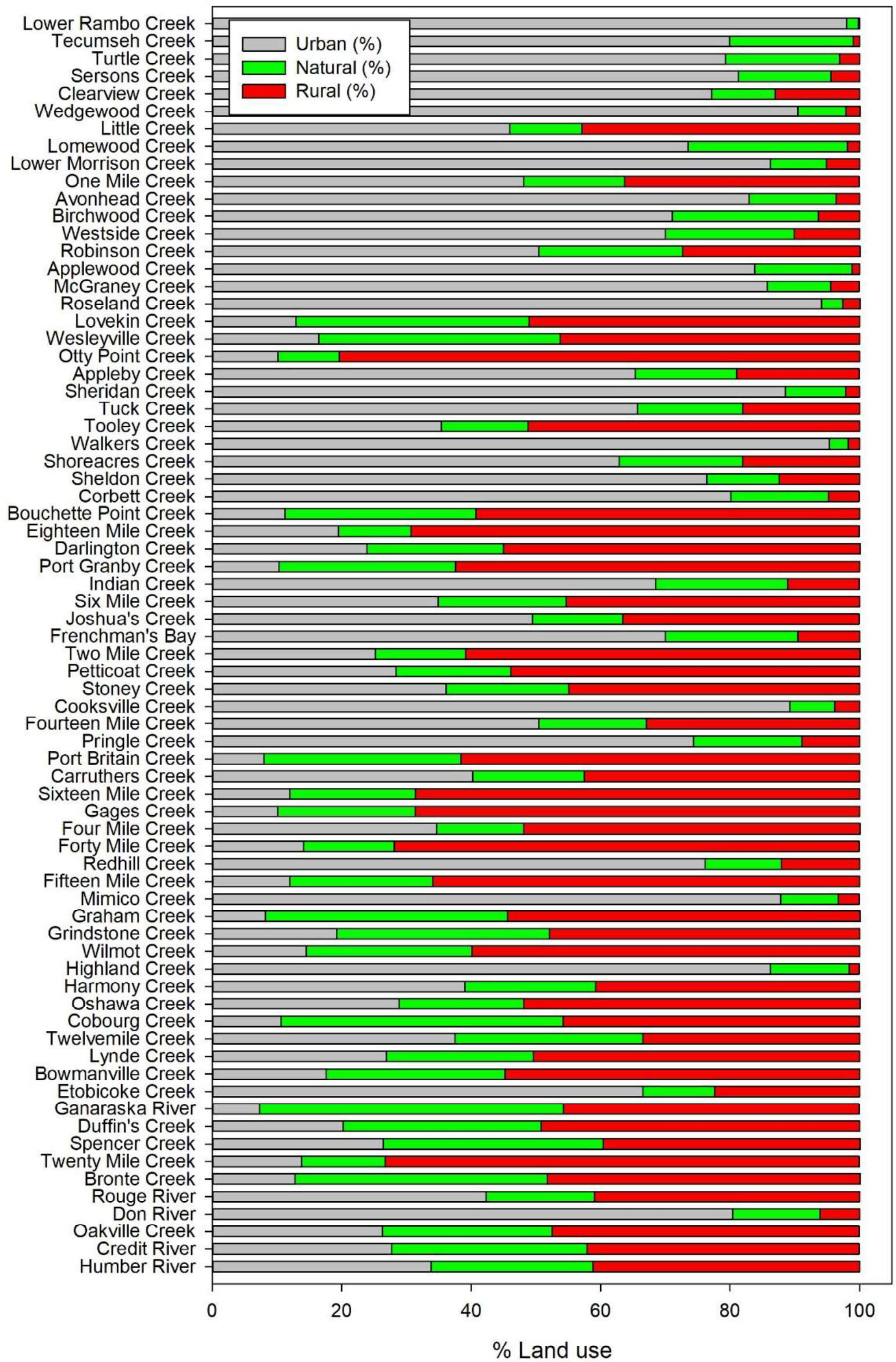


Figure 6: Land use in order of watershed drainage areas in watersheds adjacent to Western Lake Ontario.

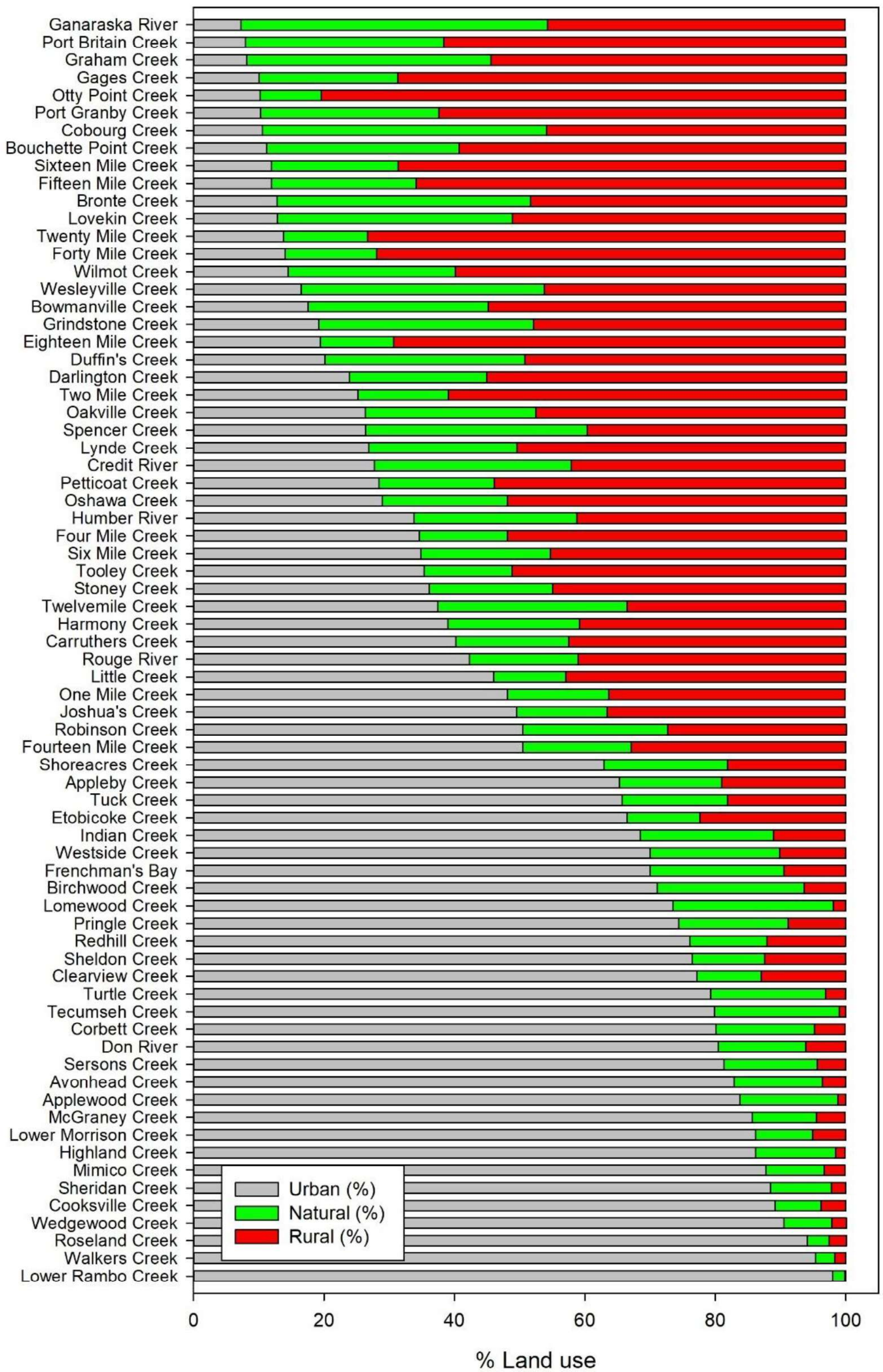


Figure 7: Land use in order of urbanization in watersheds adjacent to Western Lake Ontario.

Both discharge and water quality were available within 32 watersheds within Western Lake Ontario (Table 3) with the remainder of stations ungauged and/or unmonitored for water quality (Appendix A). Water Survey of Canada discharge record lengths generally ranged from 3 to 78 years, while Conservation Authority record lengths extended from 5 to 15 years at sites of interest. Data was not continuous at all locations with data gaps ranging from 0 to 4532 days (i.e. approximately 12 years; Table 4).

Table 3: Summary of flow and water quality stations used for loading analyses.

Tributary	Flow station code	Water Quality station code
Four Mile Creek	02HA030	6000300102
Welland Canal	02HA019	6001400102 and WE01
Twelve Mile Creek	02HA031	6001700102
Twenty Mile Creek	02HA006	6002400102
Red Hill Creek	02HA014	9000100502
Spencer Creek	02HB007 and 02HB021	CP-7
Grindstone Creek	02HB012	9000902402, GRN-4 and GRN-209
Indian Creek	Hager-Rambo Channel at QEW	NDN-31, NDN-2
Bronte Creek	02HB011	6006000702
Fourteen Mile Creek (Halton)	02HB027	6006100102
Oakville (Sixteen Mile) Creek	02HB004 and 02HB005	6006300102
Sheridan Creek	8210009	6006800102
Credit River	8090002	6007605002
Cooksville Creek	02HB030	8220004
Etobicoke Creek	02HC030	6008000602
Mimico Creek	02HC033	6008200302
Humber River	02HC003	6008301902
Don River	02HC024	6008501402
Highland Creek	02HC013	6009400202
Rouge River	02HC022 and 02HC028 (HY091 and HY095 closer but records shorter)	6009701102 and 6009701302
Petticoat Creek	HY051	PT003WM
Duffins Creek	02HC049	6010400102
Carruthers Creek	HY013	6010700202
Lynde Creek	02HC018	6010800102
Oshawa Creek	02HD008	6011100802
Bowmanville Creek	02HD006	6011600102

Tributary	Flow station code	Water Quality station code
Wilmont Creek	02HD009	6011700302
Graham Creek	Graham Creek	6011800102
Wesleyville Creek	Wesleyville Creek	Wesleyville@Lakeshore
Ganaraska River	02HD012	6012900102
Gages Creek	02HD024	6013000102
Cobourg Creek	02HD019	6013300402

Table 4: Summary of missing discharge data over entire record of use.

Tributary	Number of days with flow data	Total expected number of days	Number of missing days	Percent of missing flow data
Four Mile Creek	6119	6119	0	0
Welland Canal	12691	12784	93	0.7
Twelve Mile Creek	6118	6119	1	0.02
Twenty Mile Creek	21539	21614	75	0.3
Red Hill Creek	4634	5113	479	9.4
Spencer Creek	3287	3287	0	0
Grindstone Creek	7596	7670	74	1.0
Indian Creek	1869	1927	58	3.0
Bronte Creek	7945	7945	0	0
Fourteen Mile Creek (Halton)	7915	7915	0	0
Oakville (Sixteen Mile) Creek	20896	21276	380	1.8
Sheridan Creek	3119	3281	162	4.9
Credit River	3109	3205	96	3.0
Cooksville Creek	1284	4383	3099	70.7
Etobicoke Creek	7670	7670	0	0
Mimico Creek	7310	7670	360	4.7
Humber River	16063	16071	8	0.05
Don River	15844	16071	227	1.4
Highland Creek	15262	18628	3366	18.1
Rouge River - Little Rouge	18627	18627	0	0
Rouge River - Main Rouge	8035	8035	0	0
Petticoat Creek	5819	5844	25	0.4
Duffins Creek	12268	12268	0	0
Carruthers Creek	5836	5846	10	0.2

Tributary	Number of days with flow data	Total expected number of days	Number of missing days	Percent of missing flow data
Lynde Creek	19474	20485	1011	0.05
Oshawa Creek	3379	3379	0	0
Bowmanville Creek	16683	21215	4532	21.4
Wilmont Creek	17166	18627	1461	7.8
Graham Creek	4464	4903	439	9.0
Wesleyville Creek	3158	3882	724	18.7
Ganaraska River	17059	17059	0	0
Gages Creek	2085	2086	1	0.05
Cobourg Creek	7450	7917	467	5.9

To have a functional rating curve, at least 10 discharge measurements are required over the range of water levels measured to develop a relationship to convert level to discharge. Currently, Conservation Halton has 6 stations in close proximity to Lake Ontario where rating curves are nearly complete (Appendix A). They also have a site on Oakville Creek (Sixteen Mile) that is closer to the lake than WSC stations. A preliminary station at Indian Creek was used in this analysis as it is in a “channelized” portions of the creek; however, all results from this site should be considered provisional. In upcoming years, it will be possible to calculate loading measurements at other locations in the Halton area (e.g. Shoreacres, Sheldon, Lower Morrison, Wedgewood, and Joshawa Creeks) although estimates would benefit from the collection of winter water quality samples if the creeks flow year-round. Additionally, Central Lake Ontario Conservation Authority has an additional station with level and are developing their rating curve (Pringle Creek). They also have a discharge station on Oshawa Creek which was not used due to the record length provided; however, if flow is updated past 2015 this station could be more useful than the WSC station in the future due to its proximity to the lake.

Discharge data from Gages Creek, Cooksville Creek, and the Welland Canal are limited, particularly within recent years. Gages Creek was a part of a historical special project with data only available between 2015 and 2021 (2020-2021 remain provisional). Updated data from the Welland Canal are not currently available within the Water Survey of Canada database; Welland Canal flow is measured by an external agency. In recent years, flow is also lacking at the Don River and Lynde Creek. No future discharge is anticipated at Lynde Creek as WSC switched to measuring level only in 2021.

Water quality measurements provided by the PWQMN online portal and Conservation Authorities were merged. Many conservation authorities use the same station “name” as the PWQMN. There are two water quality stations that could be used for the Welland loadings (in the River closer to Lake Erie: 11000100502, and by the outlet to Lake Ontario: 6001400102). We opted to use the station closer to Lake Ontario. Although the station is no longer a PWQMN station (sampling ceased in 2012), Niagara Peninsula Conservation Authority has maintained sampling from 2013 to the present.

Sampling was not consistent within the different watersheds adjacent to Western Lake Ontario. Appendix B outlines the number of unique months sampled every year for each station (ranging from 2 to 12 samples per year). The majority of "priority" tributaries contain TP measurements covering all seasons. While many stations have good year-round coverage for 15-20 years, there are still a number of locations that have limited to no coverage in the winter season (e.g. Red Hill Creek, tributaries within Halton and Durham; Table 5) or limited to no winter coverage in recent years. In addition, spring coverage was limited at Indian Creek, a priority tributary, and Oshawa Creek.

Table 5: Seasonality of water quality data used in loading analyses.

Tributary	Spring	Summer	Fall	Winter
Four Mile Creek	X	X	X	X
Welland Canal	X	X	X	X
Twelve Mile Creek	X	X	X	X
Twenty Mile Creek	X	X	X	X
Red Hill Creek	X	X	X	
Spencer Creek	X	X	X	X
Grindstone Creek	X	X	X	X
Indian Creek		X	X	
Bronte Creek	X	X	X	
Fourteen Mile Creek (Halton)	X	X	X	
Oakville (Sixteen Mile) Creek	X	X	X	X
Sheridan Creek	X	X	X	X
Credit River	X	X	X	X
Cooksville Creek	X	X	X	X
Etobicoke Creek	X	X	X	X
Mimico Creek	X	X	X	X
Humber River	X	X	X	X
Don River	X	X	X	X
Highland Creek	X	X	X	X
Rouge River	X	X	X	X
Petticoat Creek	X	X	X	X
Duffins Creek	X	X	X	X
Carruthers Creek	X	X	X	X
Lynde Creek	X	X	X	X*
Oshawa Creek	X**	X	X	
Bowmanville Creek	X	X	X	X*
Wilmont Creek	X	X	X	X

Tributary	Spring	Summer	Fall	Winter
Graham Creek	X	X	X	X
Wesleyville Creek	X	X	X	X
Ganaraska River	X	X	X	X
Gages Creek	X	X	X	X
Cobourg Creek	X	X	X	X

* winter data is from the 1970s-1990s only **limited data

Flow exceedance curves

Flow exceedance curves for the 33 sites (32 tributaries) are available in Appendix C: Probability of exceedance curves; the main Rouge River and Little Rouge are shown separately. These curves illustrate that water quality samples were not adequately collected during high flow events at 29 of the 33 sites analyzed (Appendix C: Probability of exceedance curves, Table 1Table 6). In addition, there was also poor coverage of discharge throughout the curves at 7 stations.

Table 6: Maximum flow within each of the tributaries analyzed, and highest flow with a water quality sample. Loads with discharge measurements above the highest flow with a TP sample are extrapolated.

Tributary	Maximum Flow (m^3/s)	Highest flow with TP sample (m^3/s)	# flow days above highest flow with TP sample	% data extrapolated	Additional Comments
Four Mile Creek	14.8	5.6	33	0.5	
Welland Canal	304.0	272.0	26	0.2	
Twelve Mile Creek	51.6	22.4	20	0.3	
Twenty Mile Creek	115.8	80.1	12	0.1	
Red Hill Creek	30.0	9.2	25	0.5	
Spencer Creek	23.1	22.0	2	0.1	poor representation between 12 and 22 m^3/s (47 instances)
Grindstone Creek	26.7	9.0	22	0.3	
Indian Creek	5.5	2.0	16	0.9	
Bronte Creek	35.9	23.4	21	0.3	
Fourteen Mile Creek (Halton)	10.0	5.0	25	0.3	

Tributary	Maximum Flow (m^3/s)	Highest flow with TP sample (m^3/s)	# flow days above highest flow with TP sample	% data extrapolated	Additional Comments
Oakville (Sixteen Mile) Creek	127.9	68.5	20	0.1	
Sheridan Creek	10.9	6.3	7	0.2	poor representation between 2.9 and 6.2 m^3/s (85 instances)
Credit River	137.2	50.4	21	0.7	
Cooksville Creek	9.3	2.1	47	3.7	
Etobicoke Creek	109.5	68.8	3	0.04	poor representation between 32.5 and 68 m^3/s (25 instances)
Mimico Creek	33.0	11.1	57	0.8	
Humber River	241.4	191.1	1	0.01	
Don River	107.7	55.1	12	0.1	
Highland Creek	65.3	21.8	30	0.2	
Rouge River - Little Rouge	44.8	32.4	4	0.02	poor representation between 12.5 and 32 m^3/s (142 instances)
Rouge River - Main Rouge	96.1	14.1	123	1.5	
Petticoat Creek	19.4	3.6	82	1.4	
Duffins Creek	73.3	39.4	20	0.2	poor representation between 14 and 39 m^3/s (257 instances)
Carruthers Creek	7.9	2.5	105	1.8	
Lynde Creek	32.5	17.2	47	0.2	
Oshawa Creek	27.6	4.9	80	2.4	
Bowmanville Creek	70.2	14.5	46	0.3	poor representation between 4 and 19 m^3/s (459 instances)
Wilmont Creek	56.4	8.7	69	0.4	
Graham Creek	30.0	18.8	21	0.5	poor representation between 4 and 19 m^3/s (459 instances)
Wesleyville Creek	1.4	0.4	58	1.8	
Ganaraska River	140.6	24.2	76	0.4	
Gages Creek	10.3	2.6	38	1.8	
Cobourg Creek	60.2	8.3	121	1.6	

Total Phosphorus Loading estimates

Water Year

Bias statistics and loading estimates were generated for all years where flow and water quality were available except for Red Hill Creek and the Main Rouge channel where a subset of data were used (Appendix D: Bias statistics, Appendix E: Annual loading estimates). A large gap in data existed in the Redhill Creek watershed that aligned with the creation of the Red Hill Valley Parkway. With such a major land use change that lies adjacent to the creek from Hamilton Mountain to Lake, it is highly likely that the relationships between water quality and discharge changed. The expressway opened to traffic in 2007, and Water Survey of Canada data availability resumed as of 2009.

A subset of data was also used for loading estimates in the Main channel of the Rouge River. Flow-normalized loads from the entire dataset suggest underlying changes in the behavior of the watershed prior to 2002. Load estimates from the Main Rouge channel were thus completed after 2002 which improved the bias statistic from 0.5 to 0.1 (i.e. 50% down to 10%).

Loading results from 2021 and 2022, along with the bias statistic, are presented below in Table 7. In 2021 and 2022, flows ranged from 0.3 to 23 mT and 0.1 to 42 mT, respectively, at sites with available data (Table 7, Figure 8: Estimated total phosphorus loads for 2021 and 2022. Watersheds ordered from the Niagara River to Cobourg.Figure 8). Of these data, 8 sites used provisional data or are missing flow data within 2022. No data is available for the Don River, Gages Creek or the Welland Canal – three of the priority locations.

Table 7: Annual and March through July total phosphorus loading estimates for 2021 and 2022 calculated using WRTDS-K. Loads for the Main Rouge channel and Little Rouge are combined.

Tributary	Bias Statistic	2021 Estimated Annual Load (mT)	2022 Estimated Load (mT)	2021 Estimated March-July Load (mT)	2022 Estimated March-July Load (mT)
Four Mile Creek	0.0434	3.6	5.9	1.5	2.6
Welland Canal	0.00979 or −0.0253	N/A	N/A	N/A	N/A
Twelve Mile Creek	−0.112	0.8	1.5	0.3	0.5
Twenty Mile Creek	0.0404	13.1	41.5*	3.3	8.0
Red Hill Creek	−0.186	1.7	2.8	0.5	0.5
Spencer Creek	-0.145	4.3	6.4	1.9	1.9
Grindstone Creek	−0.416	1.7	2.5	1.1	0.9
Indian Creek*	0.217	0.9*	1.8*	0.6*	1.0*
Bronte Creek	−0.0918	3.2	9.1	1.9	3.7
Fourteen Mile Creek (Halton)	0.264	0.7	1.4	0.3	0.3

Tributary	Bias Statistic	2021 Estimated Annual Load (mT)	2022 Estimated Load (mT)	2021 Estimated March-July Load (mT)	2022 Estimated March-July Load (mT)
Oakville (Sixteen Mile) Creek	-0.174	22.6	22.7	10.5	10.5
Sheridan Creek	0.181	1.6	1.1 m	0.5	0.3
Credit River	0.052	7.7	11.8	2.5	4.3
Cooksville Creek	0.198	Not available	0.7	Not available	0.3
Etobicoke Creek	0.197	6.5	11.3	1.8	2.0
Mimico Creek	0.0438	5.5	5.1	2.0	0.9
Humber River	0.158	18.4 m	39.3	5.5	18.8
Don River	0.0812	21.6	Not available	9.0	Not available
Highland Creek	0.162	4.3	4.2*	1.9	1.3
Rouge River	0.0859 and 0.101	6.6	13.2*	2.6	5.8
Petticoat Creek	−0.078	0.3 m	0.5	0.1	0.2
Duffins Creek	0.15	3.8	9.1	1.9	4.6
Carruthers Creek	0.0769	0.4	1.0m	0.2	0.4
Lynde Creek	−0.00109	Not available	Not available	Not available	Not available
Oshawa Creek	-0.202	0.9	3.9	0.4	1.0
Bowmanville Creek	0.0221	2.6	6.0	1.4	3.2
Wilmont Creek	0.0638	0.9	2.5*	0.4	1.0
Graham Creek	−0.245	1.9	2.9	0.8	1.0
Wesleyville Creek	-0.0929	Not available	0.1	Not available	0.1
Ganaraska River	−0.152	4.0	6.1*	1.8	3.6
Gages Creek	−0.0465	1.1	Not available	0.6	Not available
Cobourg Creek	-0.0358	1.6	1.9*	0.6	1.0

*provisional flow used   m missing up to 5% of annual flow data

Total phosphorus loading estimates varied both between locations, and between years (Figure 8, Table 7, Appendix E: Annual loading estimates). In general, the top contributors between 2018 and 2022 were the Rouge River, Humber River, Credit River, Twenty Mile Creek, Duffins Creek, and Oakville (Sixteen Mile) Creek (Table 7, Appendix E: Annual loading estimates). The Don River was amongst the highest loads in 2018 - 2021, however, there is no data available for 2022. The smallest loaders between 2021 and 2022 were Wesleyville, Carruthers, Petticoat, Cooksville, Sheridan, Fourteen Mile (Halton), Twelve Mile, and Wilmont Creeks (Table 7, Appendix E: Annual loading estimates).

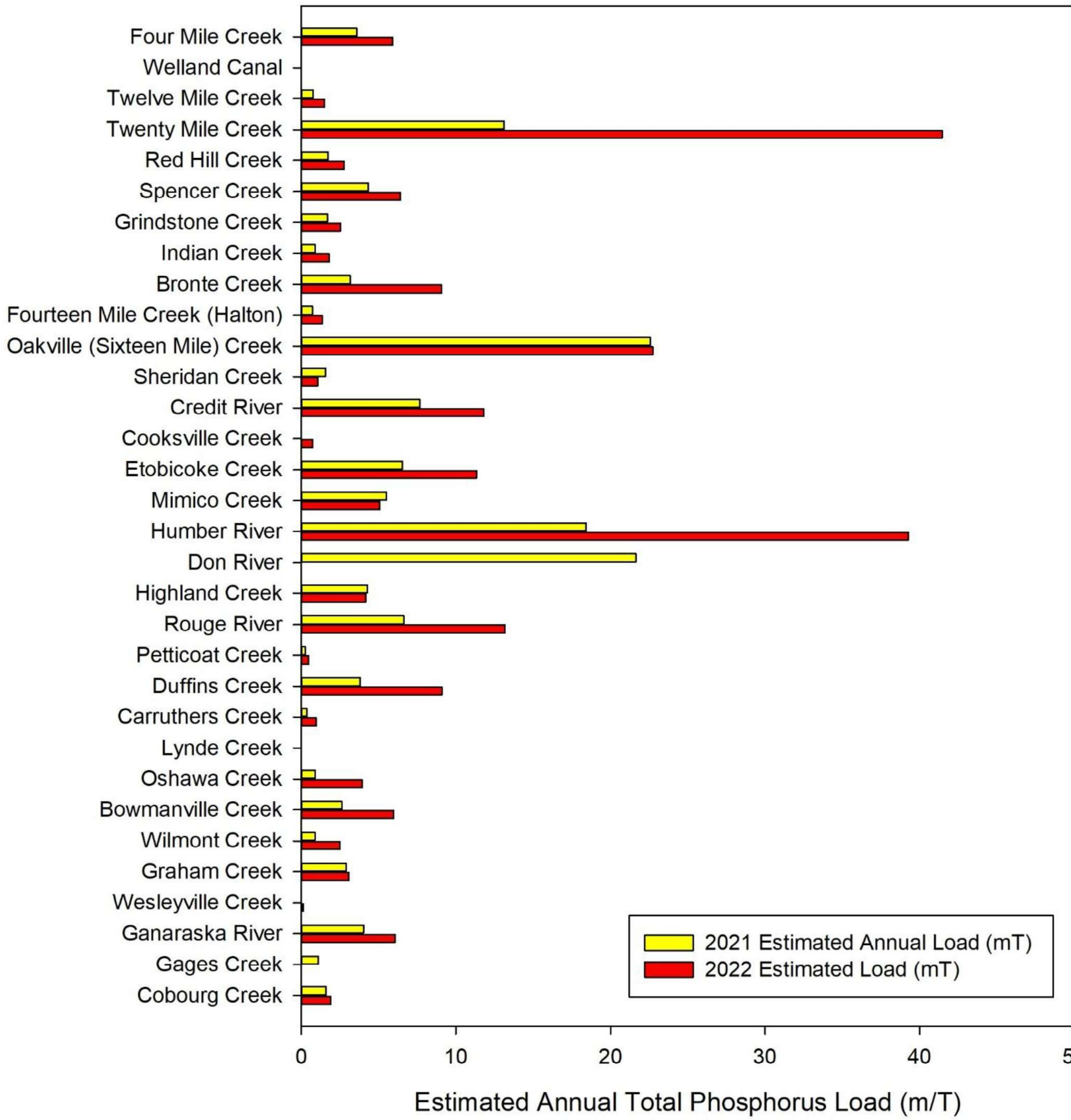


Figure 8: Estimated total phosphorus loads for 2021 and 2022. Watersheds ordered from the Niagara River to Cobourg. No loads available for the Welland Canal, Lynde Creek, 2021 Cooksville Creek, 2022 Don River, 2021 Wesleyville Creek and 2022 Gages Creek.

While the loads estimated using WRTDS-K fall within the range and order or magnitude observed in Makarewicz et al (2012), they appear to be under-estimating results. Year to year variability is expected, and likely influenced by differences in total precipitation. Probability of exceedance curves show that the high flow events are not captured well, therefore, it is highly likely that loads generated using WRTDS-K using grab samples are under-estimating actual loads. Bias statistics were variable ranging from -0.174 to 0.264, although approximately half are within +/- 0.1 (or +/- 10%) (Appendix A, Appendix D: Bias statistics, Appendix E: Annual loading estimates). Redhill Creek, Grindstone Creek, Indian Creek, Fourteen Mile Creek, Oakville Creek, Sheridan Creek, Cooksville Creek, Etobicoke Creek, Humber River, Highland Creek, Oshawa Creek and Graham Creek have the largest bias statistics (>15%) suggesting that WRTDS-K model improvements would particularly be of benefit to these watersheds. Eight of these watersheds were considered "priority" watersheds.

March – July loading estimates

The cumulative sum of loads between March and July are listed in Table 7 and ranged between 0.1 and 19 mT. Seasonal loads were on average 40% of the annual load in 2021 and 2022 (range 17 – 67%). March – July seasonal loads appear higher in tributaries that do not have water quality samples covering all seasons. No additional analysis has been done to examine the characteristics of watersheds that experience higher March - July loading.

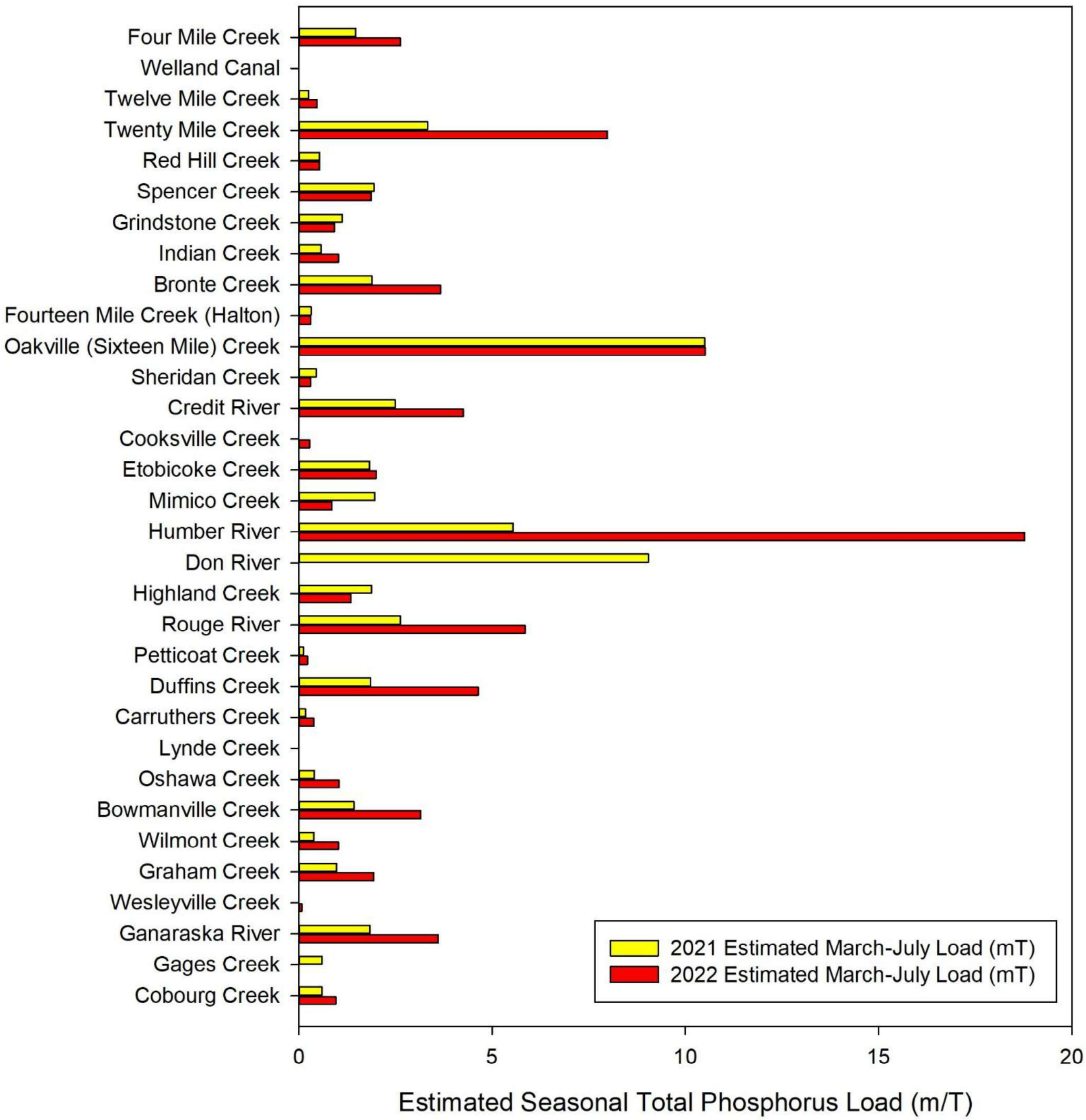


Figure 9: Seasonal (March - July) estimated total phosphorus loads from 2021 and 2022. Watersheds ordered from Niagara River to Cobourg. No loads available for the Welland Canal, Lynde Creek, 2021 Cooksville Creek, 2022 Don River, 2021 Wesleyville Creek and 2022 Gages Creek.

Seasonality

Seasonality is apparent in the load estimates (Table 8). In 2022, on average 81% of the annual load was delivered in the winter and spring; however, an average of 39% of the load was delivered during these seasons in 2021. Seasonal ranges were large between the watersheds, however, this is likely due to the poor seasonal coverage of some watersheds in addition to land use within the watersheds and stream response to precipitation (i.e. flashiness of stream). No analysis has been completed to assess characteristics of watersheds with specific seasonal patterns.

Table 8: Percent of annual load exported in each season in 2021 and 2022.

Tributary	2021 Winter (% of Load)	2021 Spring (% of Load)	2021 Summer (% of Load)	2021 Fall (% of Load)	2022 Winter (% of Load)	2022 Spring (% of Load)	2022 Summer (% of Load)	2022 Fall (% of Load)
Four Mile Creek	32	15	28	25	32	25	30	13
Welland Canal	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Twelve Mile Creek	28	14	18	39	48	24	12	16
Twenty Mile Creek	16	9	1	75	59	40	1	1
Red Hill Creek	11	7	16	67	52	28	12	8
Spencer Creek	10	17	20	54	55	35	7	3
Grindstone Creek	7	19	31	44	45	44	8	2
Indian Creek	7	35	28	30	29	46	17	8
Bronte Creek	12	17	29	41	53	45	1	1
Fourteen Mile Creek (Halton)	13	11	27	48	70	24	5	1
Oakville (Sixteen Mile) Creek	37	44	4	15	37	44	4	15
Sheridan Creek	18	19	23	40	39	23	20	18
Credit River	8	15	19	58	48	39	8	4
Cooksville Creek	N/A	N/A	N/A	N/A	58	26	11	5
Etobicoke Creek	9	14	14	63	57	15	22	7
Mimico Creek	9	20	17	54	62	13	19	6
Humber River	10	19	11	60	32	50	16	2

Don River	17	19	24	40	N/A	N/A	N/A	N/A
Highland Creek	14	18	24	43	37	18	27	19
Rouge River	10	28	22	40	47	41	9	3
Petticoat Creek	18	24	12	46	39	51	6	5
Duffins Creek	25	37	11	27	41	49	7	3
Carruthers Creek	12	25	7	56	44	47	7	2
Lynde Creek	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Bowmanville Creek	11	45	10	34	40	49	7	5
Wilmont Creek	12	29	14	45	54	39	4	4
Graham Creek	56	27	10	7	23	46	23	8
Wesleyville Creek	N/A	N/A	N/A	N/A	38	40	16	7
Ganaraska River	17	36	9	38	28	56	8	8
Gages Creek	11	35	13	40	N/A	N/A	N/A	N/A
Cobourg Creek	26	28	11	35	30	45	13	13

Data limitations

No site corrections have been made to the PWQMN data, due to the time required to assess impacts of an analytical method change on each watershed. If the analytical method currently in use by MECP provides results lower than expected, it could lead to underestimation of loads. Future works could include a more in depth analysis of phosphorus measurements pre- and post-analytical change, or an assessment on the magnitude of impact to the loadings. In the interim, it is fair to assume the loads are underestimated.

Hamilton Conservation Authority augmented their datasets using water quality from the Royal Botanical Gardens (e.g. at CP-7), however, this information was not obtained in time to acquire the additional data from the RBG. There could be future opportunities to augment datasets by following up with Conservation Authorities and other agencies.

Missing flow data will also cause underestimates of loads. A further assessment of missing flow data per year in relation to precipitation could reveal the relative importance of the missing data. If deemed necessary, annual loadings could be derived from monthly average loads vs cumulative daily loads.

The majority of water quality data used within this analysis are grab samples collected as part of a program that was not designed to calculate loads. The lack of high flow samples or event samples likely impact the loads and bias statistics generated. In addition, we noticed that the PWQMN water quality available for download had water quality results with less significant figures at times compared to results within Toronto and Region Conservation Area database (e.g. PWQMN = 0.01 mg/L, TRCA = 0.017 mg/L). It is unclear whether this occurs across all stations used, and whether other Conservation Authorities have the more detailed results in their databases.

Seasonality of samples is not consistent at locations used in the data analysis and impacts the loads generated.

Ongoing work

There are a number of projects currently underway:

1) A University of Waterloo led team has developed the POSEIDON portal of which one of their goals includes creating a dashboard to automate load calculations within the Great Lakes Basin using a combination of Weighted Regressions on Time, Discharge, and Season (WRTDS) and Random Forest (Machine Learning). To our knowledge, they currently do not plan to update their analysis to use WRTDS-K (WRTDS with a Kalman filter).

2) The Ontario Ministry of Environment, Conservation and Parks (MECP) in collaboration with other agencies have been collecting event-based data from a number of tributaries across Western Lake Ontario since 2018. A new station was added in Halton in either 2022 or 2023. MECP is collaborating with the University of Toronto to analyze event based and baseflow data to understand contributions and timing to the nearshore. A result of this work is that loadings are calculated. While the exact methods being used are unknown, presumably it will be accomplished using a hybrid EMC and regression based method. Results are anticipated within the upcoming year.

3) Historically, for smaller projects serving internal purposes with shorter timeframes, TRCA have used hybrid methods (e.g. a combination of EMC and regression based methods). TRCA have also used EMC as part of a special project in our eastern jurisdiction approximately 12 years ago.

4) While TRCA have a watershed model for Etobicoke Creek, TP was not a primary constituent within the model. However, it can be updated and calibrated for TP in the future. Currently TRCA are completing a Humber watershed model with TP loads expected for current and future climate and land use change scenarios within 2024. TRCA are also looking to model the Rouge River watershed in upcoming years.

5) Environment and Climate Change Canada are currently updating TP watershed models for Rouge River, Duffins Creek, and possibly Carruthers Creek.

6) Credit Valley Conservation have a watershed-based model for the Credit River of which further assessment is needed to determine whether TP is a constituent with loading outputs. Recent efforts to develop and apply the Hotspot Identification Tool for Sediment (HIT-S) may provide opportunities to estimate phosphorus loading.

Opportunities For Further Study

There are a number of studies and initiatives underway that are developing loading estimates and it would be helpful to compare how different sampling approaches, analysis approaches, and other factors. Opportunities to conduct comparisons when appropriate include:

- compare the WRTDS-K results from this study with the MECP event-based results and the University of Waterloo WRTDS/Machine Learning studies,
- compare the results from this study with results generated from watershed models (e.g. Credit River, Humber River, Rouge River, Duffins Creek, and Carruthers Creek), and
- compare the results from this study results with the Makarewicz et al (2012) publication.

Future comparison between these studies and approaches could provide an understanding of whether the data collected as a part of current water quality programs is sufficient in priority watersheds, and to what degree additional high discharge events can provide greater accuracy.

The Welland Canal is a complicated system. An improved understanding of sample locations and flow directions and diversions would support assessment as to whether this method is appropriate to calculate loads and assess the confidence in the resulting measurement.

The EMC method used in Makarewicz et al. (2012) assumes that event samples collected from 7 watersheds are transferable to neighbouring watersheds of similar land use. Further assessment of the appropriateness of this approach could be conducted using Hydroweight (https://glfc-wet.github.io/publication/hydroweight_2020/) which calculates distance-weighted attributes, and general additive models.

Annual loading results in this study were quite variable. Assessing the importance of additional factors that can influence loading could be of benefit to support future decision-making. Such factors could include the role and seasonal variability of past and future climate, and watershed characteristics and their nutrient sources (e.g., agricultural vs urban).

Sediment-bound phosphorus is likely an important contributor of tributary nutrients to the nearshore of Lake Ontario. It could become important to assess the seasonal delivery of particulate phosphorus to support decision-making and to target appropriate mitigation measures. An associated and important knowledge gap is whether meaningful amounts of bioavailable particulate phosphorus are delivered to the nearshore in winter and trapped by the coastal boundary layer until spring when mixing in the lake resumes. This could have implications to nutrient distribution and fate in the nearshore zone including its contribution to benthic algal growth.

Preliminary results from a few watersheds suggest that loadings are decreasing. With a base dataset available, trends in loadings could be assessed to identify other trends in nutrient loadings and other related factors. Similarly, it appears that winter and spring delivery of nutrients is quite variable and likely due to variability in temperature and snow cover. Patterns in nutrient delivery to the lake could be assessed in relation to weather, and inferences could be made considering future climate scenarios.

Within a short period of time, additional flow stations will provide data required to complete loading estimates on an additional 4 stations in Halton. Similarly, CLOCA are in the process of developing rating curves, which will increase representation within their watersheds. Toronto and Region Conservation Authority also have a number of stations closer to the lake than the WSC. Within a few years, a longer dataset will be available at current locations, and rating curves will be available at new sites. This may allow for additional tributaries to be included and generally augment the regional dataset.

Bias statistics in the study are quite variable. It could be of benefit to assess whether the watersheds are behaving differently over the data records used in the analyses and whether using subsets of data that align with major watershed changes would improve the bias observed.

CONCLUSIONS

Assembling and assessing available open data sets and routine monitoring programs has identified that there are 32 watersheds with the data resolution required for estimating Western Lake Ontario total phosphorus tributary loading using Weighted Regressions on Time, Discharge, and Season using a Kalman filter. Results are variable from year to year, however, loadings ranged from 0.1 – 41.5 mT of phosphorus in 2022, with 40% of the load (on average) entering the lake between March 1st and July 31st. Despite probability of flow exceedance curves indicating a lack of high flow water quality samples, bias statistics are less than 10% in approximately half of the stations. This study presents early and preliminary results for Western Lake Ontario tributary that can complement and compare with other methodologies and approaches to support decision-making on science and action in the Lake Ontario watershed.

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