ANALYSIS OF 2021-2023 HAMILTON TRIBUTARY MONITORING DATA: IDENTIFICATION OF POTENTIAL WATERSHED CRITICAL SOURCE AREAS AND COMPARISON OF MONITORING PROGRAM FINDINGS

Report to the Hamilton Harbour Remedial Action Plan

Prepared by

Duncan Boyd

30 June 2024

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EXECUTIVE SUMMARY

Recently completed upgrades at the Woodward Avenue Wastewater Treatment Plant (WWTP) are expected to reduce total phosphorus (TP) effluent concentrations and are projected to meet Remedial Action Plan (RAP) final loading targets. Although harbour water quality will be significantly improved, the relative influence of tributaries on harbour water quality will increase. This variability in tributary TP inputs means that, along with the influence of lake-harbour exchange on remobilization of P from sediment, variability in the timing and quantity of tributary loads will become an increasingly significant source of variability in harbour water quality. Improving tributary water quality has, therefore, become the next priority for relevant agencies and RAP partners. Not only will this reduce pollutant loads to the harbour but it will improve aquatic habitat throughout the surrounding watersheds.

Limitations on generating meaningful total P load reduction targets for Hamilton Harbour tributaries has resulted in a consensus among Hamilton Harbour Remedial Action Plan (HHRAP) agencies that it will be most productive to focus on implementing remedial actions within watersheds as part of a long-term commitment to improve management of stormwater flows and water quality throughout the surrounding watersheds. Watershed-wide reconnaissance monitoring represents an important first step in the identification of “hotspots” or Critical Source Areas (CSAs) within harbour watersheds where there is potential for improvement through application of stewardship activities and Best Management Practices (BMPs). Although the results of watershed management activities cannot be predicted with certainty, these will generally deliver multiple benefits (e.g. basement flooding protection, protection of infrastructure from stream erosion, restoration of degraded local streams and improved stream water quality, and restoration of aquatic habitat).

Analysis of tributary monitoring data generated by the City of Hamilton Surface Water Quality Program (SWQP), Hamilton Conservation authority (HCA) Cootes Tributary Monitoring, and HCA Provincial Water Quality Monitoring Network (PWQMN) over the period 2021 through 2023 was undertaken to:

a) *Identify significant geographical outliers/anomalies potentially indicative of “hotspots”;*
b) *Identify correlations among key parameters as tracers of potential sources;*
c) *Compare findings and make recommendations regarding optimized and coordinated tributary monitoring among RAP agencies; and*
d) *Make recommendations for action-oriented criteria and metrics for tracking improvements in support of a nutrient management plan for the HHRAP.*

Tributary monitoring data demonstrated the expected finding that locations with more highly urbanized upstream land uses exhibited more degraded water quality. The effects of urban environments on water quality are well documented with nutrient sources including chemical lawn fertilizer, soil, leaf litter, pet waste, construction activities, and leaking or cross connected sanitary sewers. Sources of metals include domestic and industrial sewage, combustion of solid wastes and fossil fuels, road surface runoff, corrosion of metal surfaces, tire debris and motor oil and grease. Additionally, winter road deicing programs contribute to elevated chloride concentrations in winter runoff and year-round ground water.

The ubiquitous presence of elevated chloride, *E. coli*, TP and zinc levels in urbanized watersheds renders provincial and federal water quality guidelines and standards impractical for evaluating abnormally degraded water quality in this environment. However, thresholds derived from the upper quartile of selected SWQP data provide an objective basis for flagging locations potentially meriting additional assessment. Collectively, monitoring results suggests that initial follow up efforts associated with identifying and managing anomalous sources of *E. coli* and TP can be concentrated at a small subset of program monitoring locations. More specifically, comparison of SWQP results with water quality guidelines, standards and locally derived benchmarks flagged Station CC SW9 (Chedoke Creek Mountview Falls at Railtrail Bridge) and Station UO SW1 (Red Hill Creek at Albion Falls) and BatC SW1 (Battlefield Creek at Lake Ave, Park) as high priority locations for investigation of *E. coli* sources as well as CC SW9 and CC SW3 (Chedoke Creek at Glen Rd. Outfall) as high priority locations for management of TP.

Only three of the 37 SWQP, HCA Cootes Tributary, and PWQMN sampling locations were situated close to each other so these programs do not warrant a location review as the result of redundant sampling effort. PWQMN monitoring should be maintained with the awareness that it is designed to assess long-term trends in baseflow water quality and is not compatible with SWQP and other HCA monitoring objectives. Comparison of results from these three locations where SWQP, HCA and PWQMN monitoring locations overlapped showed similar dry and wet weather medians for TP, nitrate, TSS and *E. coli* and a statistical comparison confirmed that SWQP results were comparable to higher frequency HCA results. Although PWQMN data were generally consistent with SWQP results at the Red Hill Creek Albion Falls location, the program is poorly suited for identifying potential hot spots given the low frequency of sample collection and the emphasis on rural and agricultural watersheds.

Four SWQP locations and four HCA Cootes Tributary Monitoring locations had consistently good water quality results and frequently met water quality standards and guidelines due to the predominance of upstream agricultural or natural land uses. These were: Ancaster Creek near Maple Lane Park (AC SW4); Grindstone Creek at Mill Street South (GC222 SW1); Spring Creek West of Ogilvie Street (SprC SW1); Spring Creek at John White Trail Bridge (SprC SW2); Lower Ancaster Creek Stations AC-1, AC-2 and AC-3, and the Borer's Creek station CP-18. If additional resources are required to investigate anomalies, it may be possible to reduce the sampling effort at these locations.

1. BACKGROUND AND OBJECTIVES

Recently completed upgrades, including the addition of tertiary treatment, at the Woodward Avenue Wastewater Treatment Plant (WWTP) are expected to reduce total phosphorus (TP) effluent concentrations and loads from 0.57 mg l^{-1} in 2021 (City of Hamilton 2023) to 0.15 mg l^{-1} (T. Crowley pers. com.). Relative reductions in effluent concentrations will also be achieved for ammonia from 1.29 mg l^{-1} in 2021 to 1.0 mg l^{-1} and total suspended solids (TSS) from 6.9 mg l^{-1} in 2021 to 2.0 mg l^{-1}. These significant reductions are projected to meet Remedial Action Plan (RAP) final loading targets of 72 kg d^{-1} for TP, 977 kg d^{-1} for ammonia, and 1227 kg d^{-1} for TSS (HHRAP 2018) leading to improved harbour water quality and reductions in algal productivity and oxygen consumption as well as improved water clarity.

The large reduction in effluent concentrations of TP and other parameters of concern from the Woodward Avenue WWTP will increase the average proportion of the tributary TP load to the harbour from about one third to more than one half of the reduced total TP load. Although harbour water quality will be significantly improved, the relative influence of tributaries on harbour water quality will increase. A high frequency, event-based tributary monitoring program that collected 24-hour composite samples near the mouths of Red Hill Creek, Indian Creek, Grindstone Creek, and the Desjardins Canal between July 2010 and May 2012 (Long et al. 2014, 2015) found that daily TP tributary loads varied by three orders of magnitude between wet and dry conditions, with storm events and spring freshets driving peak daily loads in urban and agricultural watersheds, respectively. It also found that brief but intense events that occurred less than 10% of the time were responsible for 50–90% of TP loads and that there was significant interannual variability in estimated total tributary P loads associated with wet versus dry years ranging from a high of 98.5 kg d-1 in 2011 to a low of 30.2 kg d-1 in 2012.

This variability in tributary TP inputs means that, along with the influence of lake-harbour exchange on remobilization of P from sediment, variability in the timing and quantity of tributary loads will become an increasingly significant source of variability in harbour water quality (Yerubandi et al. 2016; Markovic et al. 2019). The wide range of potential tributary P loads and their direct connection to variation in harbour water quality means that it is not possible to be certain that delisting targets will be met consistently in any given year despite compliance by industrial and municipal point sources with RAP loading and concentration targets. Improving tributary water quality has, therefore, become the next priority for relevant agencies and RAP partners not only to reduce pollutant loads to the harbour but to improve aquatic habitat throughout the surrounding watersheds.

High frequency, event-based tributary monitoring has also flagged several practical problems with establishing and measuring arbitrary tributary load targets (Boyd 2022). First, the dominance of flow in watershed load estimates makes it difficult to establish a baseline for tracking total P load reductions since similar flow regimes are required to diminish relative changes attributable to “wet” years versus “dry” years. There is also the difficulty of linking total watershed loads to localized remedial actions within watersheds as the benefits of local actions will be hard to discern at a watershed scale, particularly in large watersheds where the relative load reductions will be small compared with the watershed total. Finally, there is the issue of statistical power and the monitoring effort required to measure relative load reductions against a highly variable background. Statistical analysis has demonstrated that decades of monthly sampling would be required to achieve a level of statistical power capable of detecting a 10% reduction in TP loads because the natural variation of streamflow and water quality from year to year obscures this magnitude of change (Betanzo et al. 2015; Wellen et al. 2020).

These practical limitations on generating meaningful total P load reduction targets for Hamilton Harbour tributaries, have resulted in a consensus among Hamilton Harbour Remedial Action Plan (HHRAP) agencies that it will be most productive to focus on implementing remedial actions within watersheds as part of a long-term commitment to improve management of stormwater flows and water quality throughout the surrounding watersheds. This has led to support for the allocation of limited resources to water quality reconnaissance monitoring throughout harbour watersheds as being more helpful than concentrating efforts near tributary mouths solely for the purpose of estimating watershed loads of TP and other contaminants of concern. Watershed-wide reconnaissance monitoring represents an important first step in the identification of “hotspots” or Critical Source Areas (CSAs) within harbour watersheds where there is potential for improvement through application of stewardship activities and Best Management Practices (BMPs). Although the results of watershed management activities cannot be predicted with certainty, these will generally deliver multiple benefits (e.g. basement flooding protection, protection of infrastructure from stream erosion, restoration of degraded local streams and improved stream water quality, and restoration of aquatic habitat). Consideration of these multiple co-benefits within watersheds along with the resulting P load reductions to the harbour makes a compelling case to support implementation of stewardship and BMPs within harbour watersheds.

The following report analyzes recent tributary monitoring undertaken by RAP agencies to:

- Identify significant geographical outliers/anomalies potentially indicative of “hotspots”;
- Identify correlations among key parameters as tracers of potential sources;
- Compare findings and make recommendations regarding optimized and coordinated tributary monitoring among RAP agencies; and
- Make recommendations for action-oriented criteria and metrics for tracking improvements in support of a nutrient management plan for the HHRAP.

2. RECONNAISSANCE MONITORING TO IDENTIFY CSAs

Critical Source Areas (CSAs) can be defined as the intersection of high-level pollutant sources and high pollutant transport potential (USEPA 2018). Delineation of CSAs should be considered a multi-tier process in which broad-scale assessments are followed by smaller-scale assessments to refine estimates of potential load reductions within the CSA. A process overview for identifying critical source areas and BMP opportunities developed by the USEPA (2018) is shown in Figure 1.

The HHRAP has already established priorities and described connections for shifting the harbour from a eutrophic to a meso-eutrophic state through the development of process- based eutrophication modeling (Gudimov et al. 2010; 2011; Ramin et al. 2011; 2012). It has also employed intensive monitoring and modeling to characterize land use effects, delineate potential source areas and estimate relative contributions from point and non-point sources of TP (Wellen et al. 2014a; Wellen et al. 2014b; Dong et al. 2019) and consequently has reached the stage of undertaking reconnaissance monitoring to target potential CSAs and identify BMP opportunities.

Water quality characterization at the sub-watershed scale is the logical first step in the CSA identification process. Results of land use/land cover assessments can be used to design a reconnaissance survey with stations selected based on the potential to isolate specific drainage areas (i.e. sub-watersheds) or non-point source (NPS) pollutant source areas (USEPA 2018). Unlike tributary mouth assessments of larger urban areas where the effects of different subcategories of urban land uses will usually average out to

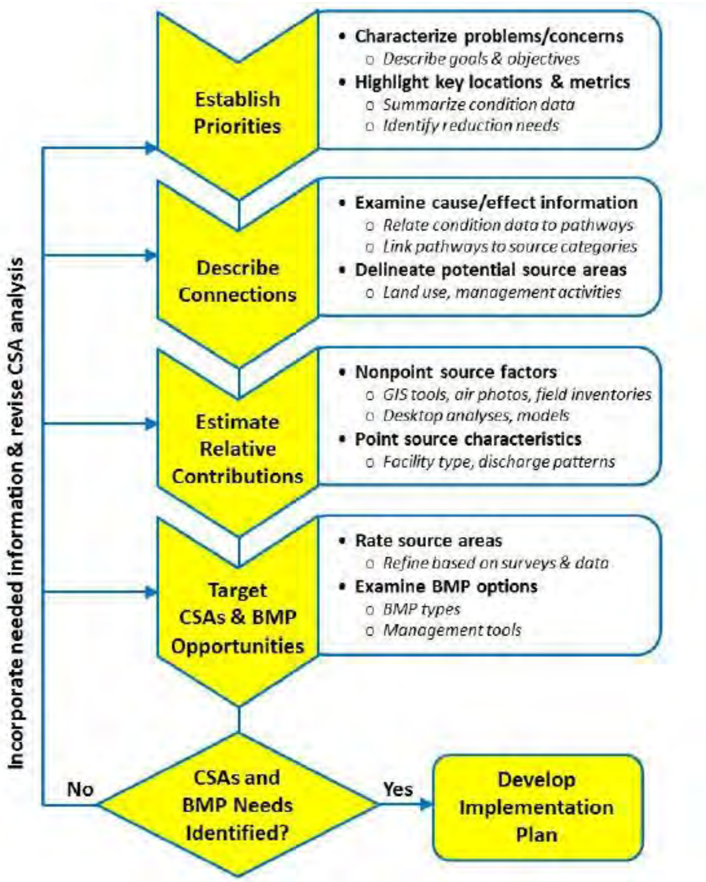

Figure 1: CSA Identification Process Overview (from USEPA 2018)

generate similar export coefficients, reconnaissance monitoring to identify CSAs will be undertaken at finer scales and will be more likely to yield highly variable and event specific results. Despite rendering this kind of data less suitable for estimating total pollutant exports, identification of sub-watershed pollutant concentration anomalies will provide useful information regarding areas that appear to be contributing more than their fair share and that merit closer scrutiny.

The CSA concept has been widely applied in rural and agricultural landscapes to isolate sediment and nutrient transfer from runoff generation to flag high-contribution regions or sub-watersheds as well as to map at a sub-field scale to manage legacy P in agricultural catchments (Thomas et al. 2016; Paton and Haacke 2020). Its application to diffuse pollution in urban environments is more challenging and less common due to the overlap of widespread pollutant transport potential and pollution supply which results in a multi-dimensional matrix of relevant source areas making it difficult to isolate the location of specific inputs (Paton and Haacke 2020). Although reconnaissance survey results may not initially lead to direct identification of manageable sources, they can focus the subsequent application of monitoring and modelling resources for source “track down” initiatives in areas where there is evidence of anomalous or disproportionate inputs of nutrients or other contaminants of concern. The goal is to identify high priority areas at a sufficiently fine scale to eventually allow implementation of a specific remedial action or policy. These scales could vary widely ranging from extremely local re-engineering of stormwater drainage from an individual property to management of runoff from large areas under construction.

3. WATERSHED SAMPLING PROGRAM OVERVIEW AND LAND USE

Recent reconnaissance monitoring has been undertaken by several agencies involved with the HHRAP. The City of Hamilton (Hamilton) has a Surface Water Quality Program (SWQP) that samples surface water throughout the City's tributaries as well as at several harbour locations. The Hamilton Conservation Authority (HCA) participates in the Provincial Water Quality Monitoring Network (PWQMN) monitoring in partnership with the provincial Ministry of the Environment, Conservation and Parks (MECP). In addition, HCA collaborates with the Royal Botanical Gardens (RBG) in monitoring tributaries that flow into the Cootes Marsh and Grindstone Creek delta as well as in these receiving waters.

The analysis in this report focuses on the tributary monitoring component which has been undertaken by Hamilton and the HCA at 38 monitoring stations[1] throughout six watersheds of varying scales that discharge directly into Hamilton Harbour or the Cootes marsh as well as in one watershed (Stoney Creek) that flows directly into Lake Ontario east of the harbour (Figure 1). Collectively the six harbour watersheds account for a little more than 80% of the total harbour watershed area of about 500 km^{-2} .

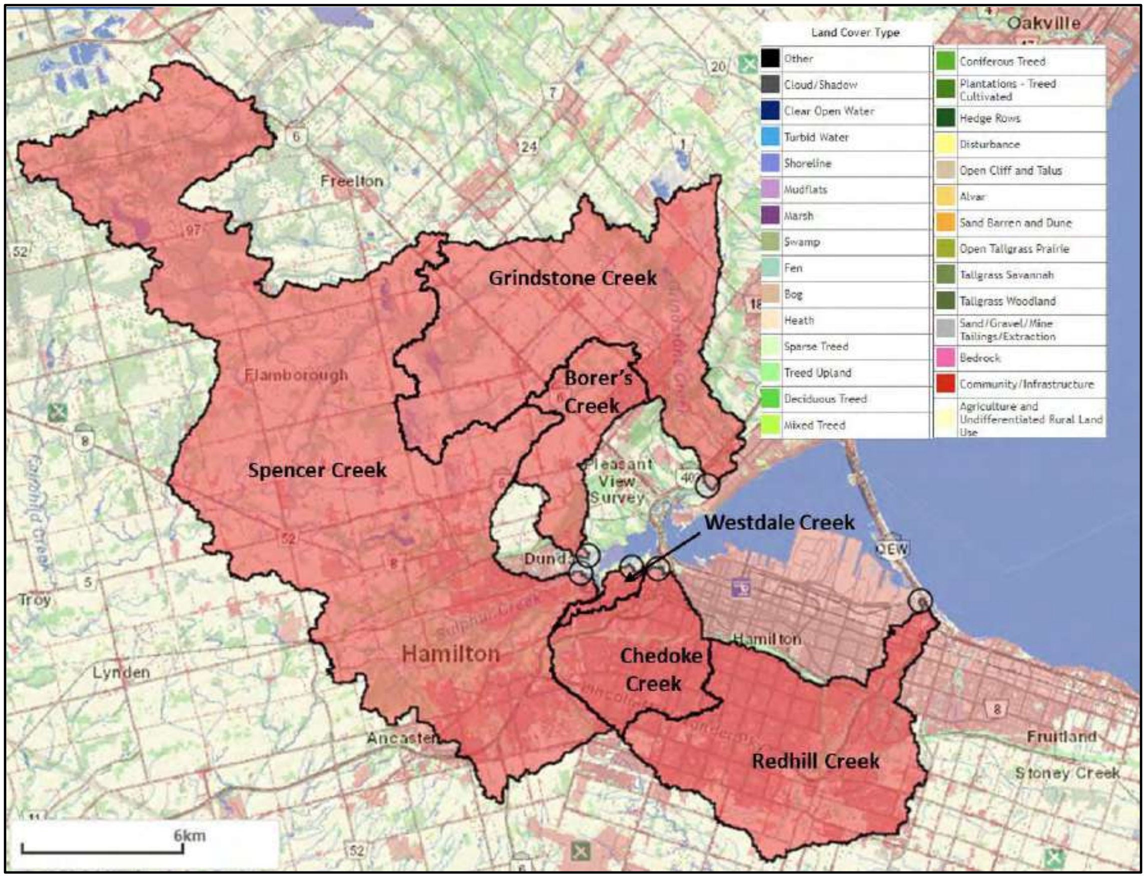

Figure 1: Watersheds with Reconnaissance Monitoring by Hamilton and HCA (watershed areas and land uses obtained using the Ontario Watershed Information Tool https://www.ontario.ca/page/ontario-watershed-information-tool-owit*)*

Table 1 summarizes the upstream land use associated with each sampling location. Between them, "Community/Urban" and "Agricultural/Rural" account for more than 80% of the land use at most of the

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[1] *RBG monitoring data collected at the mouths of four small tributaries draining into Cootes is not available for the period of interest (2021 to 2023)*

sampled locations. Urban landscapes predominate upstream at 23 of the 38 sampling locations and have been the primary focus of the City of Hamilton SWQP (15 of 21 locations). Upstream landscapes are primarily agricultural/rural at 10 of the 38 sampling locations and natural landscapes account for slightly more than either urban or agricultural upstream land uses at five locations.

Table 1: Hamilton, and HCA Tributary Monitoring Stations and Associated Upstream Land Use (harbour tributary mouth stations in upper case bold, land uses obtained using the Ontario Watershed Information Tool https://www.ontario.ca/page/ontario-watershed-information-tool-owit)

	Tributary	ID	Drainage Area (km^2)	Natural (wetland, hedgerows, treed)	Community/ Urban	Agricultural/ Rural
City of Hamilton Surface Water Quality Program	Ancaster Creek	AC SW1	6.63	14.6%	46.5%	38.6%
	Ancaster Creek	AC SW4	1.16	12.7%	15.6%	70.7%
	Grindstone Creek	GC222 SW1	70.83	26.6%	12.9%	57.6%
	WESTDALE CREEK	**LSC SW3**	**1.39**	**4.9%**	**91.6%**	**3.5%**
	Spring Creek	SprC SW2	10.59	42.0%	7.7%	48.0%
	Spring Creek	SprC SW1	12.97	44.2%	17.0%	40.9%
	CHEDOKE CREEK	**CC SW1**	**25.94**	**8.0%**	**86.0%**	**5.9%**
	Chedoke Creek	CC SW2	25.53	7.9%	86.3%	5.7%
	Chedoke Creek	CC SW3	24.76	7.9%	86.6%	5.5%
	Chedoke Creek	CC SW5	9.57	3.5%	94.2%	2.3%
	Chedoke Creek	CC SW7	<0.10	--	--	--
	Chedoke Creek	CC SW8	2.83	1.5%	96.8%	1.7%
	Chedoke Creek	CC SW9	0.39	5.7%	93.0%	1.1%
	Chedoke Creek	CC SW10	1.28	32.6%	44.2%	23.2%
	RED HILL CREEK	**RHV SW1**	**65.03**	**8.0%**	**70.0%**	**20.9%**
	Red Hill Creek	RHV SW2	62.34	8.4%	69.4%	21.7%
	Red Hill Creek	RHV SW3	60.16	8.5%	68.8%	22.1%
	Red Hill Creek	RHV SW4	38.89	6.4%	71.7%	21.8%
	Red Hill Creek	UO SW1	24.53	4.6%	63.2%	32.0%
	Battlefield Creek *	BatC SW1	6.06	14.9%	34.2%	50.2%
	Battlefield Creek *	BatC SW2	4.72	15.6%	19.4%	64.1%
Hamilton CA Cootes Monitoring	Ancaster Creek	AC-1	40.79	37.5%	36.1%	26.1%
	Ancaster Creek	AC-2	37.59	37.5%	35.4%	26.7%
	Ancaster Creek	AC-3	37.58	37.5%	35.4%	26.7%
	Ancaster Creek	AC-5	8.12	13.9%	53.7%	32.1%
	SPENCER CREEK	**CP-7**	**222.22**	**33.8%**	**15.5%**	**49.5%**
	BORERS CREEK	**CP18**	**19.48**	**19.0%**	**23.4%**	**56.7%**
	Chedoke Creek	CP-11	25.56	8.0%	86.2%	5.7%
	Chedoke Creek	CC-3	9.58	3.5%	94.1%	2.3%
	Chedoke Creek	CC-5	7.59	14.7%	72.9%	12.4%
	Chedoke Creek	CC-7	0.03	4.3%	62.2%	33.4%
	Chedoke Creek	CC-9	7.71	1.0%	96.5%	2.5%
Hamilton CA PWQMN	Spencer Creek	9000800502	162.56	32.4%	8.6%	57.4%
	Spencer Creek	9000800602	129.31	35.9%	5.4%	57.7%
	Spencer Creek	9000800702	52.01	48.8%	3.1%	47.7%
	GRINDSTONE CREEK	**9000902402**	**79.44**	**28.3%**	**13.7%**	**55.4%**
	Red Hill Creek	9000100402	24.61	4.6%	63.1%	32.2%
	Red Hill Creek	9000100502	58.33	8.5%	68.4%	22.7%

** Outside Harbour Watershed* | Predominantly Urban | Predominantly Agricultural | Relatively Natural

Urban land uses are well documented to have degraded water quality and associated nutrient and contaminant loads (Ellis and Mitchell 2006; Petrucci et al. 2014). Nutrient sources include atmospheric deposition, chemical lawn fertilizer, soil, leaf litter, pet waste, construction activities, and leaking or cross connected sanitary sewers (Carey et al. 2013; Yang and Lusk 2018; Patton and Haacke 2020). Urbanized watersheds exhibit a flashier hydrological response to wet weather events than agricultural or natural landscapes due to their greater proportion of impervious surfaces (Leopold 1968, Hutchinson et al. 2011, Lamera et al. 2014). Wet weather flow management can be expected to yield a range of benefits (e.g. reduced basement flooding in areas serviced by combined systems, protection of stormwater conveyance infrastructure, erosion and flood control) in addition to improving water quality through the reduction of contaminants such as sediment, nutrients, heavy metals, pathogens, and organic compounds (Ellis 2009; Rentachintala et al. 2022; Vogel and Moore 2016; Petrucci et al. 2014). For this reason, stormwater management continues to be a priority for municipalities in the implementation of Best Management Practices (BMPs), green infrastructure (GI), and Low Impact Development (LID).

4. CITY OF HAMILTON SWQP DATA ANALYSIS

Initiated in May 2021 the City of Hamilton's Surface Water Quality Program (SWQP)[2] has included sampling at approximately monthly intervals over multiple tributary locations throughout watersheds in their jurisdiction with most of these discharging into Hamilton Harbour. The analysis in this report uses results from 21 locations, 19 of which are in watersheds discharging into the harbour (Table 1, Figure 2).

The SWQP Framework was designed to provide a holistic understanding of its receiving waters and the potential impacts from various assets within the storm and wastewater collection and treatment system. The goals were to: (a) assess ambient baseline water quality conditions, (b) determine the effects of infrastructure on water quality during seasonal fluctuations, wet/dry, and storm weather events, and (c) identify water quality anomalies meriting further investigation (Hamilton 2021).

The total number of samples collected between March 2021 and November 2023 ranged from 16 to 34 depending on location. Wet weather samples were classified as ≥ 4mm of recorded precipitation within a 24-hour period prior to sampling and ranged from 4 to 19 depending on location (Table 2).

Figure 2: City of Hamilton Surface Water Quality Program (SWQP) Tributary Monitoring Locations

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[2] *https://www.hamilton.ca/home-neighbourhood/water-wastewater-stormwater/stormwater-management/surface-water-quality-program*

Table 2: SWQP Tributary Monitoring Locations and Number of Samples

Station ID	Description	Total Samples	Dry Samples	Wet Samples
AC SW1	Ancaster Creek at roadway culvert	21	14	7
AC SW4	Ancaster Creek near Maple Lane Park	21	14	7
BatC SW1	Battlefield Creek at Lake Ave Park	31	12	19
BatC SW2	Battlefield Creek at Battlefield Museum	29	10	19
CC SW1	Chedoke Creek at Princess Point Bridge	30	21	9
CC SW10	Chedoke Creek at Outfall near 130 Daffodil Crescent	31	21	10
CC SW2	Chedoke Creek at Kay Drage Park Bridge	31	20	11
CC SW3	Chedoke Creek at Glen Rd. Outfall	31	21	10
CC SW5	Chedoke Creek at Storm Sewer Outfall (HCA Stn. CC-3)	34	22	12
CC SW7	Chedoke Creek near Beddoe Drive	31	21	10
CC SW8	Chedoke Creek Downstream of Storm Sewer Outfall	16	12	4
CC SW9	Chedoke Creek Mountview Falls at Railtrail Bridge	30	20	10
GC222 SW1	Grindstone Creek at Mill Street South	21	12	9
LSC SW3	Westdale Creek near Westdale Aviary	23	15	8
RHV SW1	Red Hill Creek Pier 24-25 Bridge at Eastport Drive	27	19	8
RHV SW2	Red Hill Creek Bridge at Eastport Drive Beach Blvd.	32	18	14
RHV SW3	Red Hill Creek Between Rennie and Brampton	32	18	14
RHV SW4	Red Hill Creek at Red Hill Valley Trail Bridge	32	18	14
SprC SW1	Spring Creek West of Ogilvie Street	21	14	7
SprC SW2	Spring Creek at John White Trail Bridge	21	14	7
UO SW1	Red Hill Creek at Albion Falls	34	20	14

Phase I of this multi-phase Framework (2021 to 2024) focused on establishing a monthly surface water quality program within the watersheds that were initially identified as high priority. A recently released amendment to the Phase I sample locations (Hamilton 2023) documents a decision to discontinue sampling at in-harbour locations and re-allocating resources to add approximately 17 new surface water locations throughout the watersheds starting in 2023. Results of Phase I data from this CSA report will also inform Phase II expansions and future Phase III decisions for capital Investment and strategic Sewer Use By-Law enforcement, by prioritizing areas of concern for targeted property inspection. Phase I sample analysis by the City of Hamilton Environmental Laboratory included nutrients, suspended solids, and metals as well as field-based measurements for various physical parameters such as temperature, pH, and conductivity (see Appendix A for complete list).

The SWQP provides a consistent and extensive data set for the period 2021 to 2023 and consequently provides considerable scope for data analysis (see Appendix B for complete data set). The data were first screened to remove results with a high frequency of “non detects” and a short list of key parameters were then refined from the remaining results based on a comparison with federal or provincial water quality standards[3] and examination of correlations among parameters. The goal was to select a representative range of distinct parameters for multivariate analysis and comparison with water quality objectives and guidelines. This process resulted in the following shorter list of key parameters: chloride (Cl), *E. coli*, nitrate as N (NO_3), total phosphorus (TP), total suspended solids (TSS), unionized ammonia

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[3] *Canadian Water Quality Guideline for the Protection of Aquatic Life (CWQG) and Provincial Water Quality Objectives (PWQO)*

(NH_3), copper (Cu), iron (Fe), lead (Pb) and zinc (Zn). This spectrum of analytes covers a range of both dissolved and particulate associated contaminants as well as *E. coli* which is a tracer of human or animal fecal material. Although soluble P (dissolved o-Phosphate as P) samples were not collected as frequently as these other key parameters, and many of the results were below detection limits, results are included in the data listing (Appendix B) because of the insights they provide at certain locations.

Data were also separated into "wet" and "dry" weather results using a criterion of ≥ 4mm of recorded precipitation within a 24-hour period prior to and during the sampling date. Table 2 provides additional detail regarding station location and a breakdown of the number of dry weather and wet weather samples collected. The distribution of wet and dry data for each location was assessed using the Shapiro-Wilk normality test and the results showed non-normal (typically right-skewed) distributions for most parameters at all locations so data were summarized and analyzed using non-parametric statistics [4]. The use of rank-based statistics also avoided issues associated with censored data and allowed results below method detection limits (MDLs) to be represented as 0.5 MDL without the corresponding skew in distribution biasing the results.

4.1 SWQP Multivariate Analysis

Table 3 shows dry weather median concentrations for the key parameters. Principal Component Analysis (PCA)[5] and Hierarchical Clustering (HC)[6] on all parameters was undertaken to identify any multivariate patterns in the data (see Appendix B). The PCA showed no indication of local anomalies in the relationship among parameters apart from Station CC SW9; a location that drains a small residential area (0.39 km^{-2}) south of Scenic Drive and north of Mohawk Drive. It demonstrated a wide separation from other locations on PC_1 vs. PC_2 biplot (Figure 4). Much of this separation was driven by extremely elevated dry weather *E. coli* and Zn concentrations (see Table 3). The HC analysis also showed CC SW9 as a one-station cluster distinct from other sampling locations (Figure 5). The dry weather cluster analysis also picked out the Spring Creek, Grindstone Creek and Ancaster Creek locations which had the highest water quality.

For wet weather (Table 4), the PCA showed Stations CC SW9 and CC SW8 as widely separated from other locations (Figure 3). Station CC SW9 was most influenced by elevated nutrients (TP, NH_3, NO_3), *E. coli* and Zn whereas Station CC SW8 was most influenced by extremely high concentrations of other metals (Cu, Fe) and TSS (see Table 4). The wet weather HC analysis (Figure 4) showed CC SW8 and CC SW9 as one-station clusters distinct from all other locations but also showed CC SW9 as being relatively close to RHV SW1 and RHV SW2 (the two locations near the mouth of Red Hill Creek).

Although wet weather results at CC SW8 may have been biased by the small sample size (n=4) it is apparent that the wet weather spikes in Cu, Fe, TSS, and Zn occurred in three of the four sampling events over a wide range of dates so the anomalies were not driven by a single extreme event. Although sampling location CC SW8 is only about 500m east of CC SW9, it drains a larger area (2.83 km^{-2}) from the escarpment north of Sanatorium Falls to Stone Church Road south of the Lincoln M. Alexander Parkway and is evidently reflecting different wet weather sources from CC SW9 and all other locations.

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[4] *medians, quartiles, Kruskal-Wallis ANOVA with Dunn's multiple comparison and Bonferroni correction*

[5] *XLSTAT PCA type: Correlation, Standardization: (n), Rotation: Varimax / Number of factors = 2*

[6] *XLSTAT HC Euclidean distance, Ward's linkage*

Table 3: Dry weather median concentrations at SWQP stations

Station Location	N	Cl (mg/l)	E. coli log (MPN/100 ml)	Nitrate as N (mg/l)	TP (mg/l)	TSS (mg/l)	Unionized Ammonia as NH3 (ug/l)	Cu (mg/l)	Fe (mg/l)	Pb (mg/l)	Zn (mg/l)
AC SW1	14	**190**	**1695**	**0.72**	**0.040**	**3.6**	**0.85**	**0.0008**	**0.230**	**0.0002**	**0.005**
AC SW4	14	**128**	**94**	**0.60**	**0.072**	**4.1**	**1.35**	**0.0008**	**0.458**	**0.0002**	**0.011**
BatC SW1	12	**244**	**3480**	**1.26**	**0.309**	**4.3**	**3.65**	**0.0027**	**0.261**	**0.0005**	**0.011**
BatC SW2	10	**205**	**105**	**0.39**	**0.056**	**4.9**	**0.15**	**0.0024**	**0.280**	**0.0006**	**0.005**
CC SW1	21	**224**	**140**	**1.87**	**0.238**	**15.0**	**18.80**	**0.0035**	**0.616**	**0.0011**	**0.029**
CC SW2	20	**275**	**309**	**2.44**	**0.298**	**10.5**	**13.10**	**0.0032**	**0.520**	**0.0008**	**0.026**
CC SW3	21	**323**	**820**	**2.88**	**0.312**	**3.2**	**2.80**	**0.0033**	**0.142**	**0.0003**	**0.024**
CC SW5	22	**257**	**688**	**2.74**	**0.248**	**3.0**	**0.80**	**0.0022**	**0.148**	**0.0005**	**0.033**
CC SW7	21	**132**	**1730**	**2.76**	**0.249**	**7.6**	**0.50**	**0.0036**	**0.263**	**0.0004**	**0.026**
CC SW8	12	**421**	**139**	**1.46**	**0.044**	**8.3**	**0.30**	**0.0025**	**0.399**	**0.0008**	**0.022**
CC SW9	20	**161**	**19388**	**4.56**	**0.479**	**3.1**	**9.00**	**0.0036**	**0.100**	**0.0008**	**0.153**
CC SW10	21	**267**	**27**	**0.27**	**0.041**	**1.2**	**0.20**	**0.0012**	**0.085**	**0.0002**	**0.043**
GC222 SW1	12	**112**	**109**	**1.54**	**0.047**	**3.8**	**0.33**	**0.0018**	**0.191**	**0.0002**	**0.004**
LSC SW3	15	**597**	**93**	**0.42**	**0.034**	**2.2**	**0.40**	**0.0004**	**0.198**	**0.0001**	**0.001**
RHV SW1	19	**208**	**276**	**15.30**	**0.202**	**6.4**	**13.60**	**0.0037**	**0.438**	**0.0005**	**0.028**
RHV SW2	18	**266**	**473**	**17.10**	**0.303**	**6.8**	**4.80**	**0.0046**	**0.605**	**0.0005**	**0.032**
RHV SW3	18	**298**	**668**	**0.88**	**0.065**	**4.3**	**1.00**	**0.0025**	**0.153**	**0.0004**	**0.020**
RHV SW4	18	**313**	**316**	**1.00**	**0.040**	**1.8**	**0.60**	**0.0020**	**0.060**	**0.0002**	**0.025**
SprC SW1	14	**79**	**119**	**0.15**	**0.029**	**5.4**	**0.18**	**0.0014**	**0.320**	**0.0002**	**0.002**
SprC SW2	14	**59**	**48**	**0.08**	**0.028**	**10.1**	**0.15**	**0.0014**	**0.444**	**0.0003**	**0.002**
UO SW1	20	**342**	**2490**	**1.50**	**0.078**	**4.4**	**1.55**	**0.0021**	**0.232**	**0.0005**	**0.148**
Objectives/ Guidelines	***PWQO***	***--***	***200****	***--***	***0.030***	***--***	***19.00***	***0.0050***	***0.300***	***0.0050***	***0.020***
	CWQG	***120***	***--***	***3.00***	***--***	***25.0***	***--***	***--***	***--***	***--***	***--***

Table 4: Wet weather median concentrations at SWQP stations

Station Location	N	Cl (mg/l)	E. coli log (MPN/100 ml)	Nitrate as N (mg/l)	TP (mg/l)	TSS (mg/l)	Unionized Ammonia as NH3 (ug/l)	Cu (mg/l)	Fe (mg/l)	Pb (mg/l)	Zn (mg/l)
AC SW1	7	**180**	**1050**	**0.72**	**0.053**	**2.8**	**0.45**	**0.0010**	**0.328**	**0.0003**	**0.006**
AC SW4	7	**124**	**120**	**0.40**	**0.111**	**5.3**	**1.20**	**0.0015**	**0.704**	**0.0003**	**0.012**
BatC SW1	19	**186**	**4610**	**0.76**	**0.223**	**5.1**	**4.20**	**0.0049**	**0.345**	**0.0010**	**0.014**
BatC SW2	19	**244**	**866**	**0.57**	**0.097**	**5.9**	**0.60**	**0.0029**	**0.435**	**0.0008**	**0.008**
CC SW1	9	**252**	**998**	**1.06**	**0.257**	**34.0**	**12.15**	**0.0042**	**0.980**	**0.0026**	**0.025**
CC SW2	11	**232**	**1050**	**1.60**	**0.318**	**18.2**	**12.60**	**0.0038**	**0.572**	**0.0015**	**0.023**
CC SW3	10	**285**	**1446**	**2.10**	**0.311**	**4.4**	**4.20**	**0.0039**	**0.201**	**0.0004**	**0.020**
CC SW5	12	**259**	**1084**	**2.77**	**0.320**	**10.7**	**0.43**	**0.0041**	**0.357**	**0.0012**	**0.030**
CC SW7	10	**101**	**2834**	**2.59**	**0.243**	**6.5**	**0.28**	**0.0039**	**0.244**	**0.0005**	**0.017**
CC SW8	4	**43**	**8532**	**0.55**	**0.294**	**152.0**	**1.20**	**0.0183**	**11.600**	**0.0116**	**0.100**
CC SW9	10	**195**	**16041**	**4.88**	**0.524**	**5.4**	**9.95**	**0.0052**	**0.152**	**0.0010**	**0.188**
CC SW10	10	**207**	**221**	**0.47**	**0.090**	**2.1**	**1.50**	**0.0016**	**0.273**	**0.0003**	**0.039**
GC222 SW1	9	**91**	**260**	**1.11**	**0.087**	**10.9**	**0.80**	**0.0024**	**0.547**	**0.0006**	**0.008**
LSC SW3	8	**582**	**112**	**0.46**	**0.031**	**2.7**	**1.00**	**0.0005**	**0.221**	**0.0001**	**0.001**
RHV SW1	8	**182**	**4700**	**11.45**	**0.383**	**12.4**	**3.10**	**0.0050**	**0.923**	**0.0011**	**0.036**
RHV SW2	14	**189**	**1570**	**13.15**	**0.403**	**12.6**	**1.30**	**0.0052**	**0.675**	**0.0006**	**0.030**
RHV SW3	14	**191**	**3990**	**0.71**	**0.121**	**17.6**	**2.80**	**0.0040**	**0.581**	**0.0016**	**0.041**
RHV SW4	14	**226**	**2774**	**1.50**	**0.078**	**15.8**	**1.90**	**0.0043**	**0.787**	**0.0013**	**0.048**
SprC SW1	7	**78**	**517**	**0.20**	**0.028**	**7.4**	**0.30**	**0.0018**	**0.667**	**0.0003**	**0.006**
SprC SW2	7	**71**	**127**	**0.16**	**0.040**	**10.1**	**0.40**	**0.0015**	**0.499**	**0.0002**	**0.002**
UO SW1	14	**323**	**5023**	**1.23**	**0.109**	**8.3**	**3.15**	**0.0041**	**0.368**	**0.0010**	**0.123**
Objectives/ Guidelines	***PWQO***	***--***	***200****	***--***	***0.030***	***--***	***19.00***	***0.0050***	***0.300***	***0.0050***	***0.020***
	CWQG	***120***		***3.00***	***--***	***25.0***	***--***	***--***	***--***	***--***	***--***

**Geometric mean N > 5*

Apart from these two sampling locations, the multivariate assessment did not reveal any systemic patterns capable of providing insights into different types of sources. This reflects the generally homogeneous nature of the urban landscape that dominates this sampling program.

An examination of the general pattern of results across all sampling locations in Tables 3 and 4 does, however, reveal better water quality conditions at the few stations with a higher proportion of relatively natural land cover. Wet and dry sample results collected from the Spring Creek locations (SprC SW1, SprC SW2) with >40% natural landcover had notably lower results for Cl, *E. coli*, NO_3 and TP. Since the collective assessment of multiple parameters masks single parameter anomalies, individual results for these parameters are assessed below.

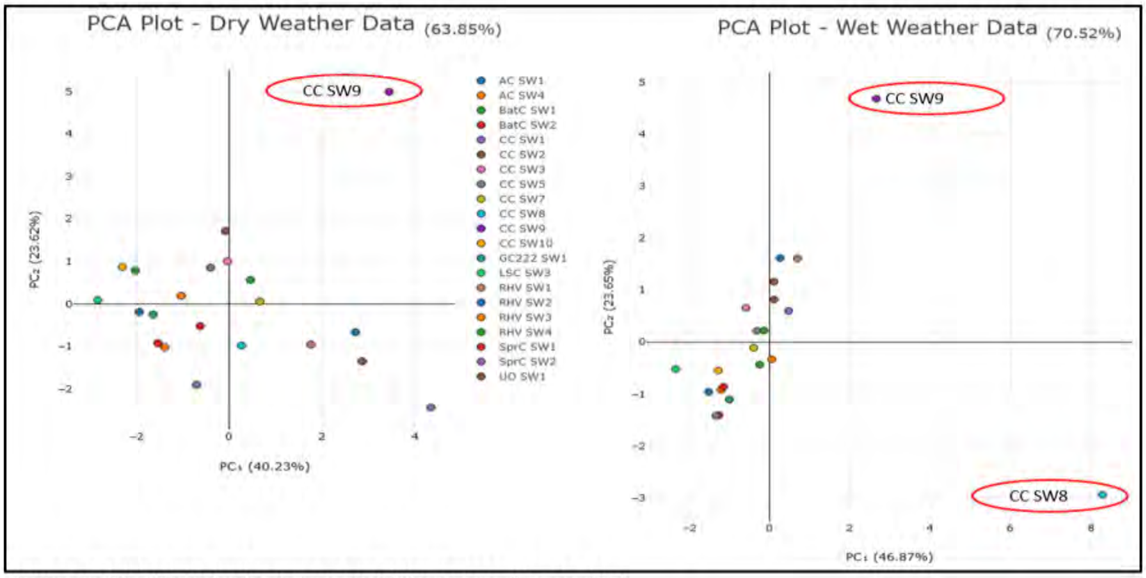

Figure 3: SWQP Principal Component Biplot Scores (PC_1 vs. PC_2)

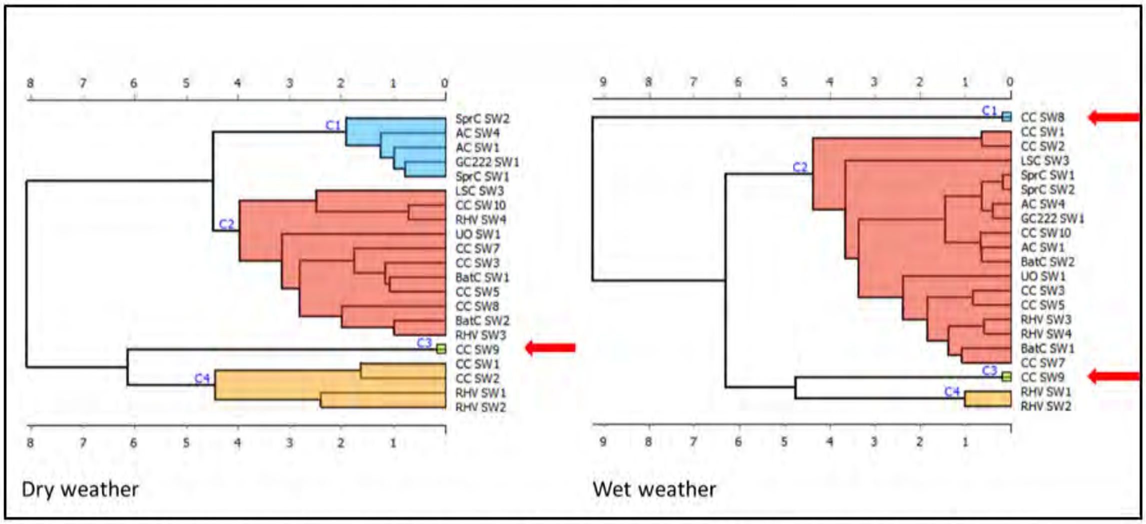

Figure 4: SWQP Hierarchical Clustering Dendrogram (Top 4 clusters, Euclidean Distance, Ward's linkage)

4.2 SWQP Univariate Analysis

4.2.1 Chloride

Comparison of dry weather Cl results using a non-parametric ANOVA (Kruskal-Wallis) showed results for Station LSC SW3 to be significantly greater ($p<0.05$) than 12 of the other 20 locations, and results for four locations to be significantly less ($p<0.05$) than nearly half of the locations (see Appendix B). Figure 5 shows the distribution of dry weather 25th percentile (near minimum) results for chloride which correspond well to the ANOVA results.

The pattern of elevated dry-weather chloride concentrations is strongly indicative of the influence of winter de-icing activity and the well-documented long-term increase in the salinity of groundwater and its subsequent effect on summer dry weather water quality in urban tributaries (Lawson and Jackson 2021; Howard 2023). The significant anomaly observed at Station LSC SW3 (Westdale Creek near Westdale Aviary) suggests this location is even more susceptible to this influence than other locations. This may reflect the fact that this is a relatively small (1.39 km^{-2}), low-lying, and highly urbanized (92%) watershed, affected by runoff from Hwy. 403, which functions as a collection point for groundwater flow towards the harbour.

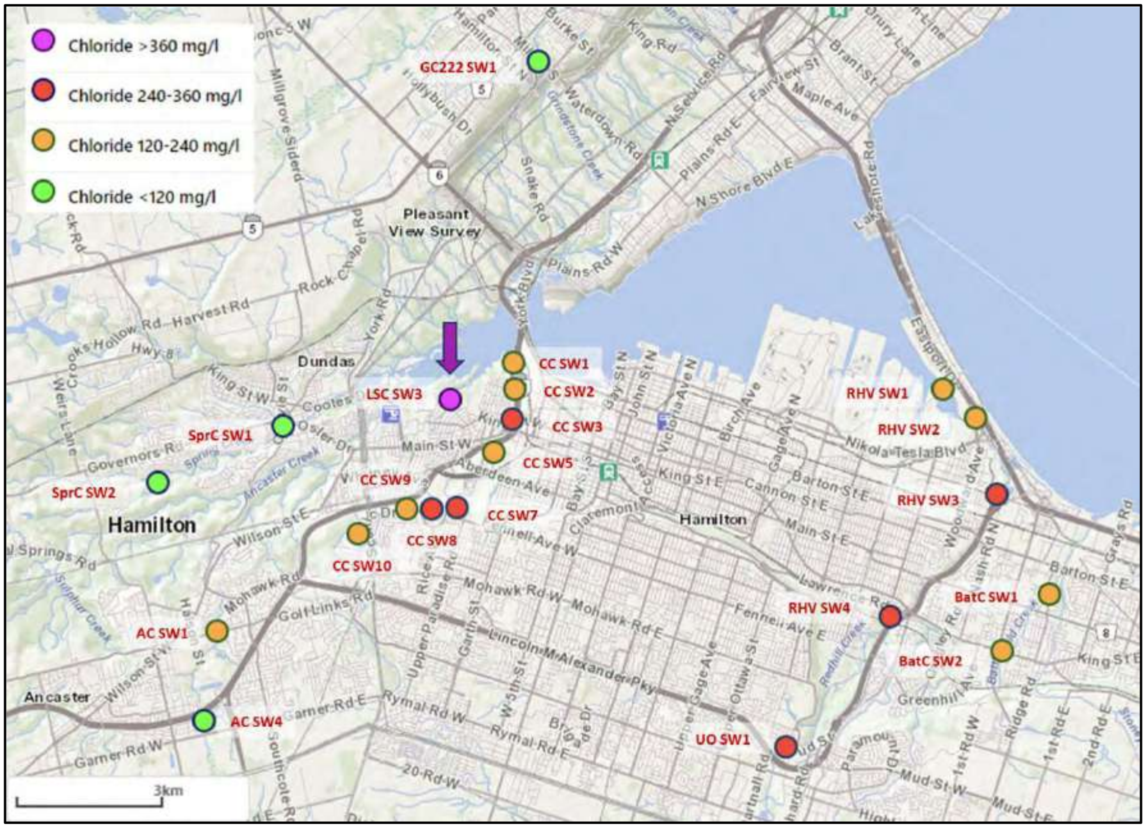

Figure 5: SWQP Dry weather 25th percentile chloride concentrations

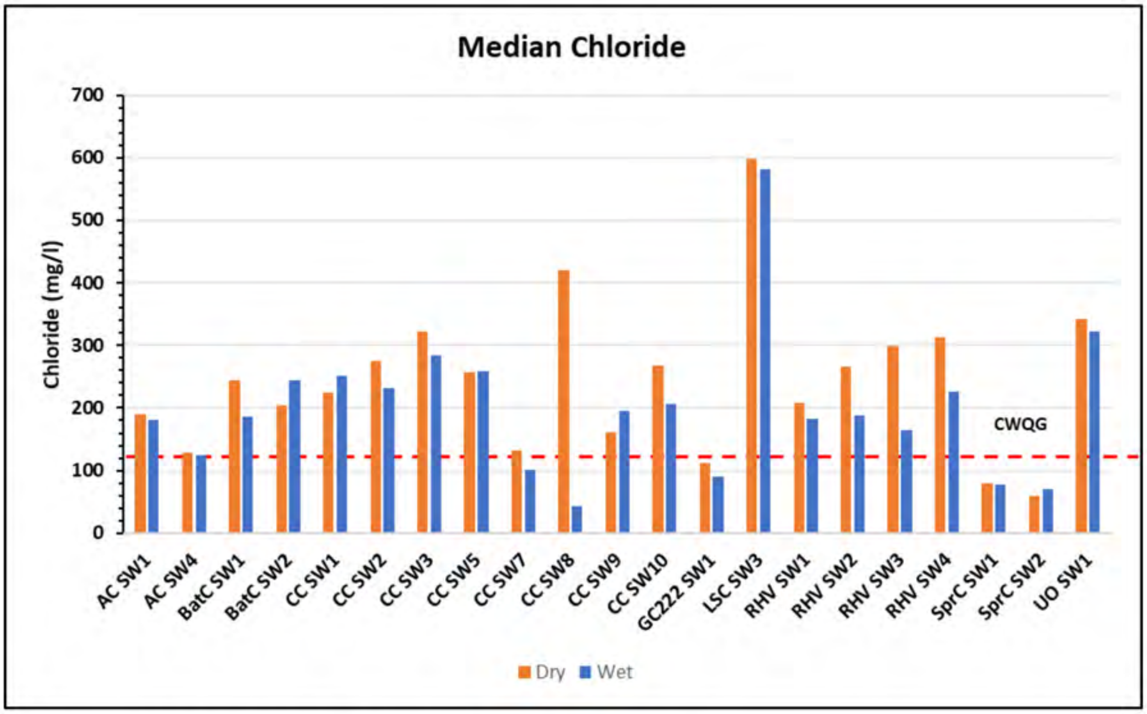

Figure 6: SWQP Dry and Wet Weather Median Chloride concentrations

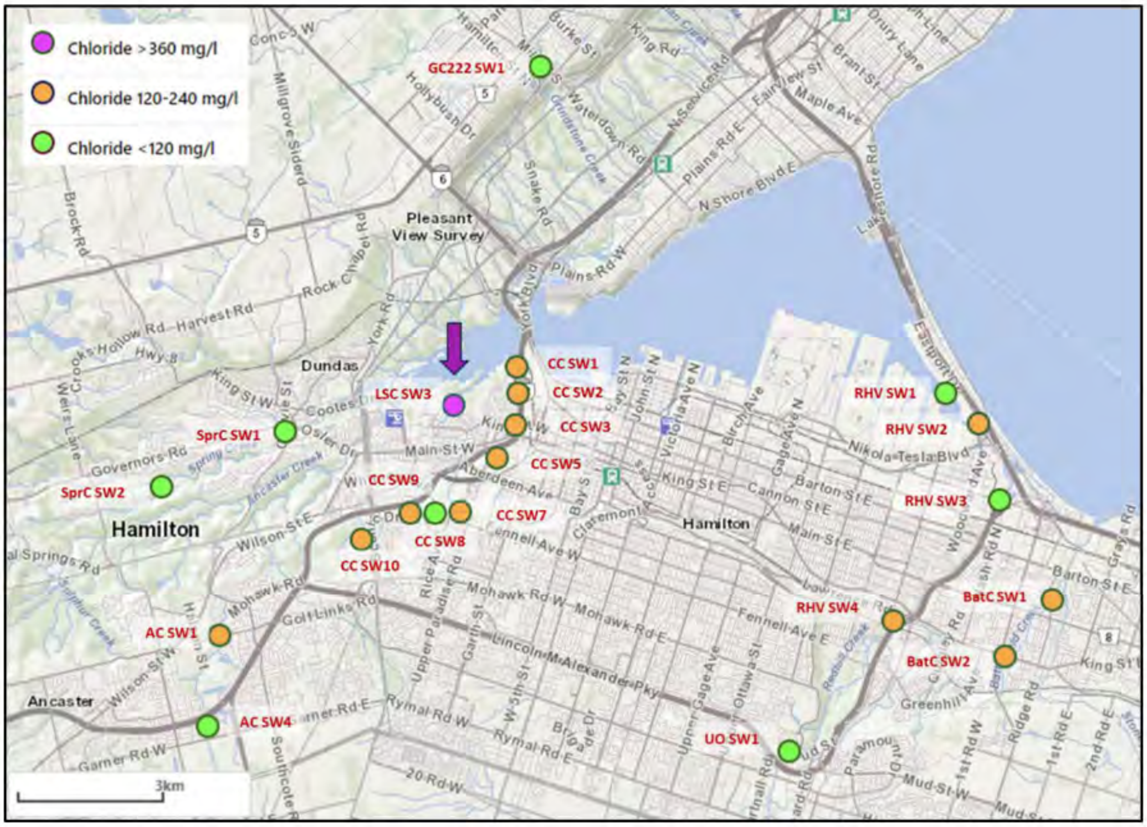

Figure 7: SWQP Wet weather 25th percentile chloride concentrations

Wet weather median chloride concentrations were slightly lower at 16 of the 21 locations (Figure 6). This dilution effect was most pronounced at CC SW8 where the wet weather median concentration was an order of magnitude lower than during dry weather. This dilution effect is consistent with winter season increases in the salinity of runoff and subsequent effect on groundwater. Comparison of median wet weather Cl results using a non-parametric ANOVA showed more homogeneous conditions with relatively more locations having concentrations below the CWQG of 120 mg l^{-1} (see Appendix B). The significance of the Westdale Creek anomaly was less than during dry weather but concentrations remained significantly greater than six of the other 20 locations. The 25th percentile map (Figure 7) also illustrates this finding.

4.2.2 *E. Coli*

Dry weather median *E. coli* results ranged widely across SWQP locations with many locations having median counts below 200 MPN/100 ml, confirming an absence of dry weather inputs. Comparison of dry weather *E. coli* results using a non-parametric ANOVA on $\log_{10}$ transformed data[7] flagged an anomaly with counts at location CC SW9 significantly greater ($p<0.05$) than 16 of the other 20 sites (Appendix B). Examination of Table 3 shows a median *E. coli* count of more than 19,000 MPN/100ml at CC SW9 which is strongly suggestive of a cross connection to a sanitary sewer given the absence of runoff related sources. This anomaly is well illustrated by the 25th percentile dry weather count map (Figure 8). Although CC SW9 is by far the most significant anomaly, the ANOVA flagged a few other locations with greater than typical dry weather counts which generally correspond to the locations flagged in the 25th percentile map (AC SW1, BatC SW1, CC SW7, UO SW1) and which are also somewhat indicative of sewage-related inputs.

Wet weather median E. coli counts were higher (in some cases substantially so) at all but two sampling locations (AC SW1 and CC SW9) although the reduction was relatively slight in both instances (Table 4; Figure 9). The ANOVA did not identify any single geographical anomaly during wet weather which reflects the effect of urban runoff generating more homogeneous degraded conditions across all locations (Figure 10, Appendix B). These elevated wet weather numbers are not unusual in urban settings (Raboni et al. 2016; Lee et al. 2020) where sources can include exfiltration from sanitary sewers, as well as dog, ruminant, and avian feces (Deidrich et al. 2023) particularly during the first-flush following a rain event.

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[7] *Statistical analysis of* E. coli *data is typically undertaken on log transformed data due to the high degree of variability and tendency for positively skewed results.*

Figure 8: SWQP Dry weather 25th percentile E. coli *counts*

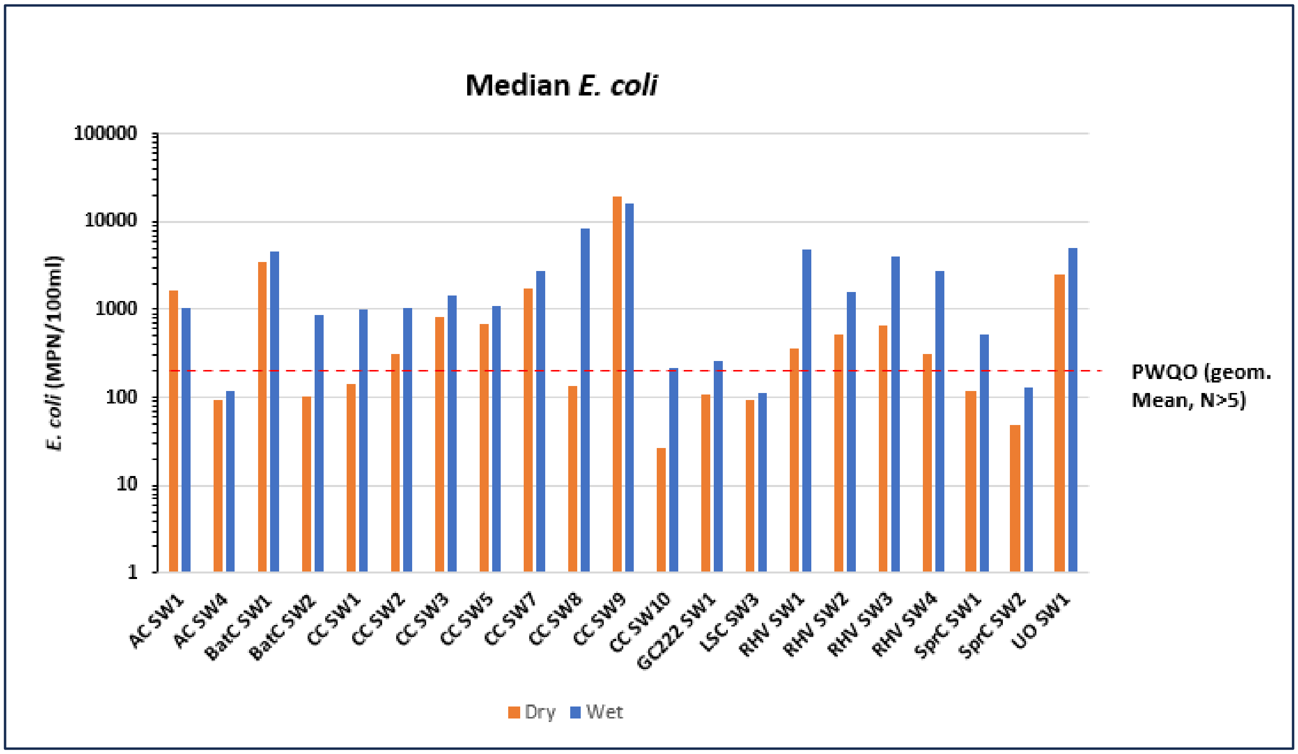

Figure 9: SWQP Dry and Wet Weather Median E. Coli *counts*

Figure 10: SWQP Wet weather 25th percentile E. coli *counts*

4.2.3 Nitrate

Inspection of Table 3, Table 4 and Figure 11 shows that despite some variation across SWQP sampling locations, all but three locations met the CWQG of 3.0 mg $NO3^{-}$-N^{-1} (Nitrate as N) for long term exposure of aquatic life. Once again it is notable that the lowest concentrations were observed at the Spring Creek locations having the highest proportion of natural landcover. The most significant anomalies occurred at locations RHV SW1 and RHV SW2 immediately downstream from the Woodward Avenue WWTP outfall in lower Red Hill Creek. Typical concentrations of NO_3 in secondary and tertiary WWTPs with ammonia nitrification range between 10 – 20 mg l^{-1} (CCME 2012) so the WWTP discharge influence is particularly apparent during dry weather.

Wet weather concentrations were generally lower than, or similar to, dry weather concentrations and this dilution effect is similar to that observed for chloride. This suggests that dry weather baseflow is influenced by groundwater where nitrate tends to accumulate because of its high stability and solubility. Station CC SW9 had both wet and dry weather concentrations greater than 3.0 mg l^{-1} with wet weather concentrations being slightly greater than dry weather.

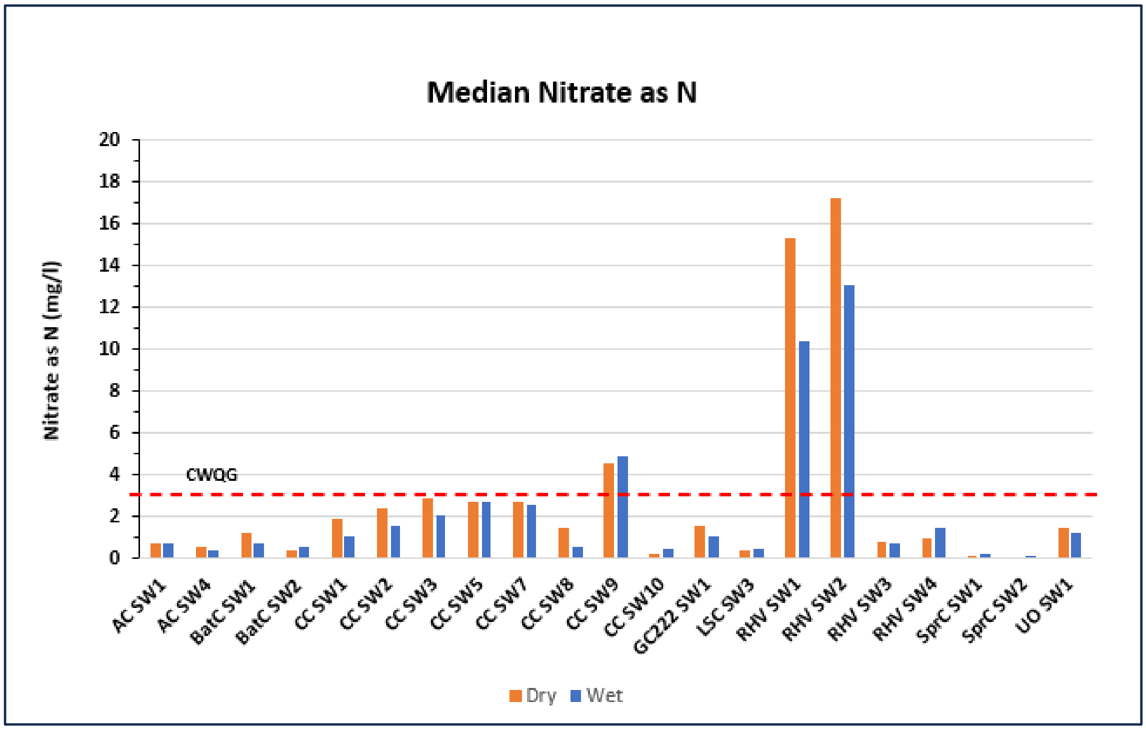

Figure 11: SWQP Dry and Wet Weather Median Nitrate concentrations

4.2.4 Total Phosphorus

Dry weather median TP concentrations varied widely across SWQP sampling locations (Table 3). Results ranged from less than 0.030 mg l^{-1} at the relatively natural Spring Creek locations, to 0.479 mg l^{-1} at Station CC SW9. The non-parametric ANOVA for dry weather TP shows nine sampling locations as being significantly greater ($p<0.05$) than most of the sampling locations and these correspond to the stations with dry-weather median TP concentrations greater than 0.200 mg l-1 (see Table 3, Appendix B). This pattern is well illustrated by the map of dry weather 25th percentile concentrations which shows both the prevalence of elevated dry weather TP concentration in Chedoke Creek as well as the extremely low concentrations at the more natural Spring Creek and Westdale Creek locations (Figure 12). The ANOVA and map also show the lower Battlefield Creek location (BatC SW1) to have had significantly greater TP concentrations than the location further upstream (BatC SW2).

Sampling Station CC SW9 had the most extreme dry weather TP results which were highly correlated with NO_3 ($r^2 = 0.8026$) but less so with E. coli ($r^2 = 0.4420$) or ammonia ($r^2 = 0.2274$) (Appendix B). Examination of the available soluble P data (dissolved o-Phosphate as P) for this location shows concentrations of about 70% to 97% of TP concentrations. Soluble P was also highly correlated with NO_3 which suggests a similar dry weather source of soluble nutrients either in the local groundwater or associated with a sanitary sewer connection. It is also notable that station CC SW8 did not show the elevated dry weather TP concentrations observed at the adjacent locations CC SW7 and CC SW9. Evidently dry weather concentrations of soluble P in groundwater are not a pervasive issue in this area making it likely that results reflect more local sources. The other elevated TP concentrations in lower Red Hill Creek downstream of the Woodward Ave. WWTP discharge generally reflect a lower proportion of

Figure 12: SWQP Dry weather 25th percentile Total Phosphorus concentrations

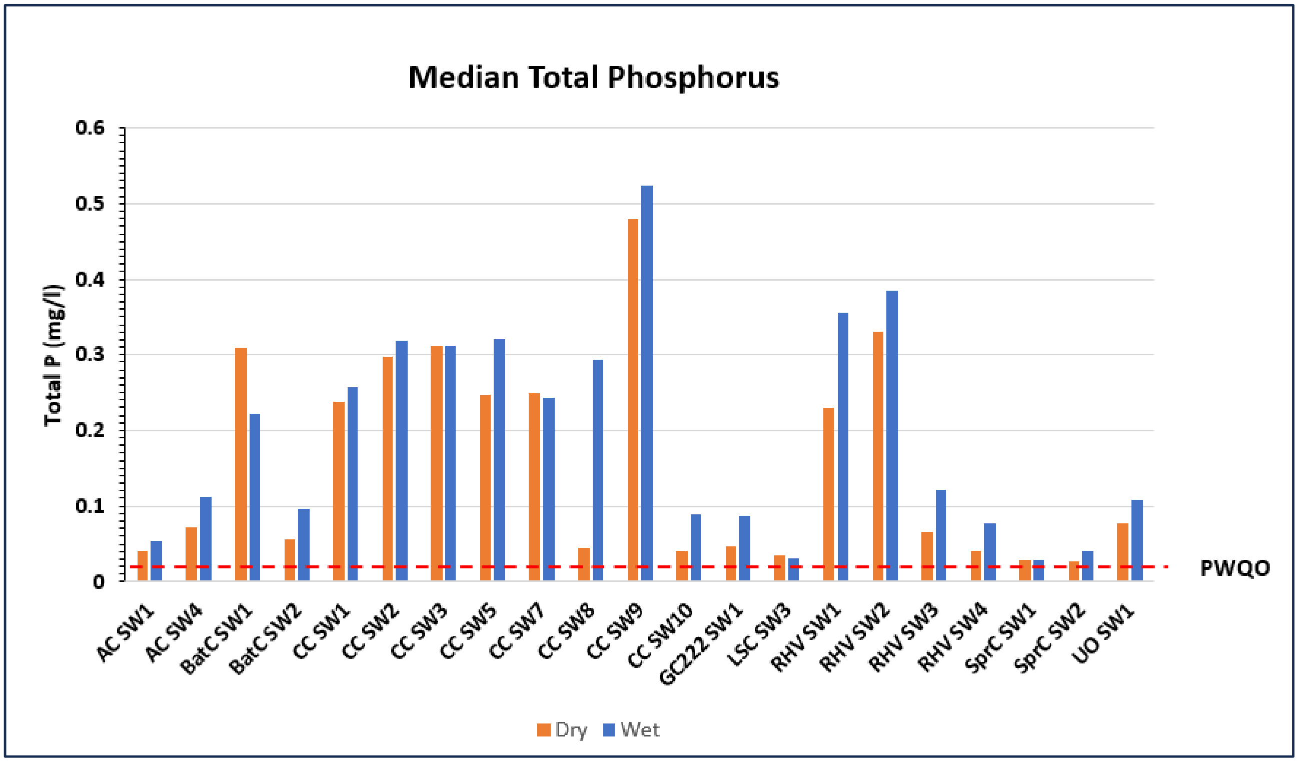

Figure 13: SWQP Dry and Wet Weather Median Total Phosphorus concentrations

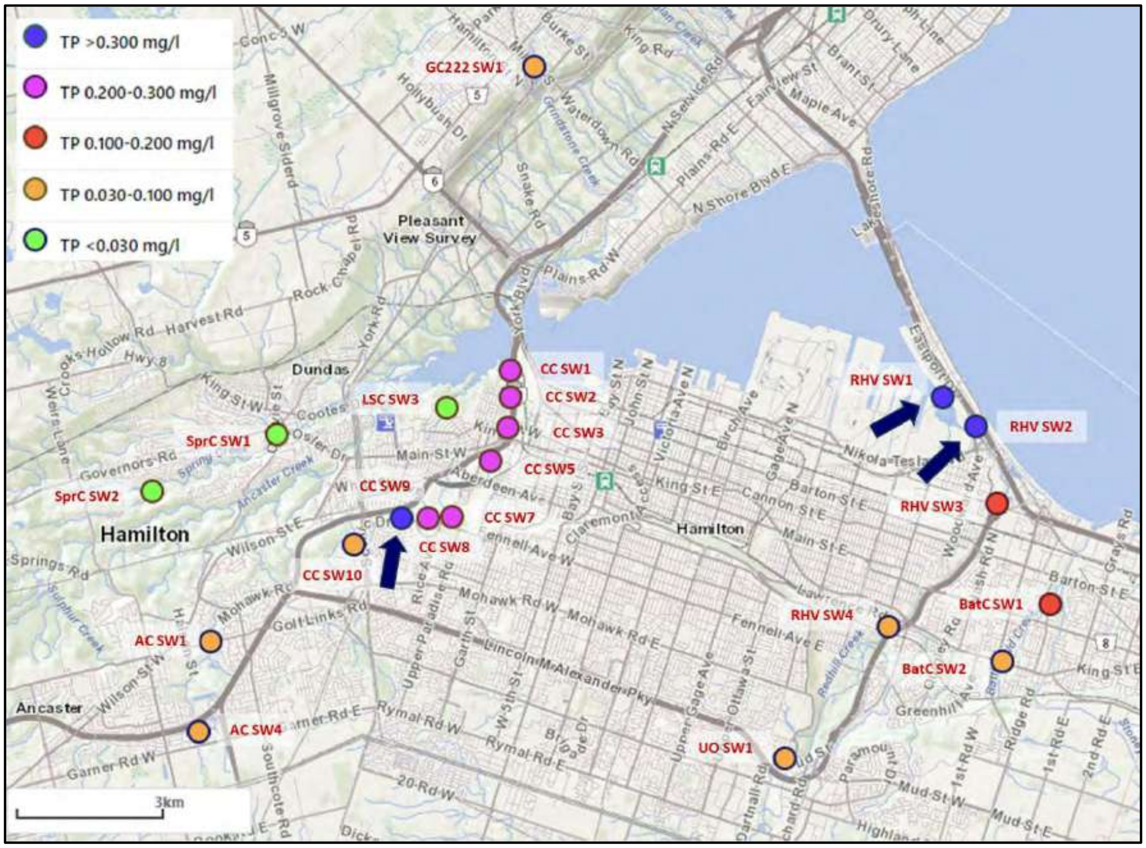

Figure 14: SWQP Wet weather 25th percentile Total Phosphorus concentrations

soluble P (20% – 80%) than observed at the Chedoke Creek locations. This suggests a different kind of dry weather input, in this case the influence of treated effluent.

Wet weather median TP concentrations were generally greater than during dry weather (Table 4, Figure 13). Interestingly, soluble P still accounted for 85% to 100% of TP at the elevated Chedoke Creek stations CC SW5, CC SW7 and CC SW9 but, as with dry weather results, for only 20% to 60% at RHV SW2. The non-parametric ANOVA showed Station CC SW9 and RHV SW2 as being significantly greater ($p<0.05$) than half the other stations (Appendix B) and these locations are flagged in the wet weather 25th percentile map (Figure 14) along with RHV SW1 which was significantly greater than five other locations. The relatively large increase in TP concentrations observed at CC SW8 may have been an artifact of the relatively few wet weather samples collected ($n=4$) but three of the four observations were greater than 0.250 mg l^{-1} so the anomaly was not skewed by a single extreme event.

4.2.5 Unionized Ammonia as NH_3

Although median dry weather concentrations of NH_3 were below the CWQG of 19 µg l^{-1} at all locations they varied widely from less than 0.2 µg l^{-1} at the Spring Creek locations, to 18.8 µg l^{-1} at Station CC SW1 in lower Chedoke Creek (Table 3). The non-parametric ANOVA showed Stations CC SW1, CC SW2, CC SW9 and RHV SW1 as having significantly greater ($P<0.05$) concentrations than more than half of the sampling locations. These locations are flagged in the map of 25th percentile concentrations (Figure 15) which also highlights Stations CC SW3 and RHV SW2 (which the ANOVA showed as having NH_3 concentrations significantly greater than eight and nine of the sampling locations) and BatC SW1 (significantly greater than six locations).

Unionized or total ammonia was not strongly correlated with TP, or *E. Coli* at lower Chedoke Creek and Red Hill Creek locations (CC SW1, CC SW2, RHV SW1, RHV SW2), or at CC SW9 which suggests that ammonia concentrations at these locations were not linked to sewage-related sources. Neither were they correlated with chloride or nitrate, so there was no strong link to a groundwater influence on baseflow. One possible explanation is the presence of particulate ammonia in leachate from the 25-hectare west Hamilton landfill adjacent to lower Chedoke Creek which closed in 1975 (now Kay Drage Park). High levels of ammonia were detected in leachate from the closed Rennie and Brampton Street landfills in lower Red Hill Creek in the late 1990s resulting in a leachate control project completed in 2003 (Dillon Consulting Ltd. 2003). Vehicle exhaust emissions have also been identified as an under-recognized source of ammonia in heavily urbanized environment as the by-product of catalytic converter technologies designed to stop emissions of other vehicular pollutants like nitric oxides (Walters et al. 2022; Cao et al. 2022). It is possible that these dry weather results were linked to vehicle dry weather deposition from the adjacent 400 series highways (Hwy. 403 and Queen Elizabeth Way).

In contrast to this, ammonia at the downstream location in Battlefield Creek (BatC SW1), which is not adjacent to a 400 series highway, or near a closed landfill, was strongly correlated with TP (r^2= 0.6420) and *E. coli* (r^2= 0.9637). These correlations, and the anomalously high dry weather E. coli count, suggest that the elevated dry weather ammonia concentrations at this location were linked to a sewage-related input.

Figure 15: SWQP Dry weather 25th percentile unionized ammonia as NH_3 concentrations

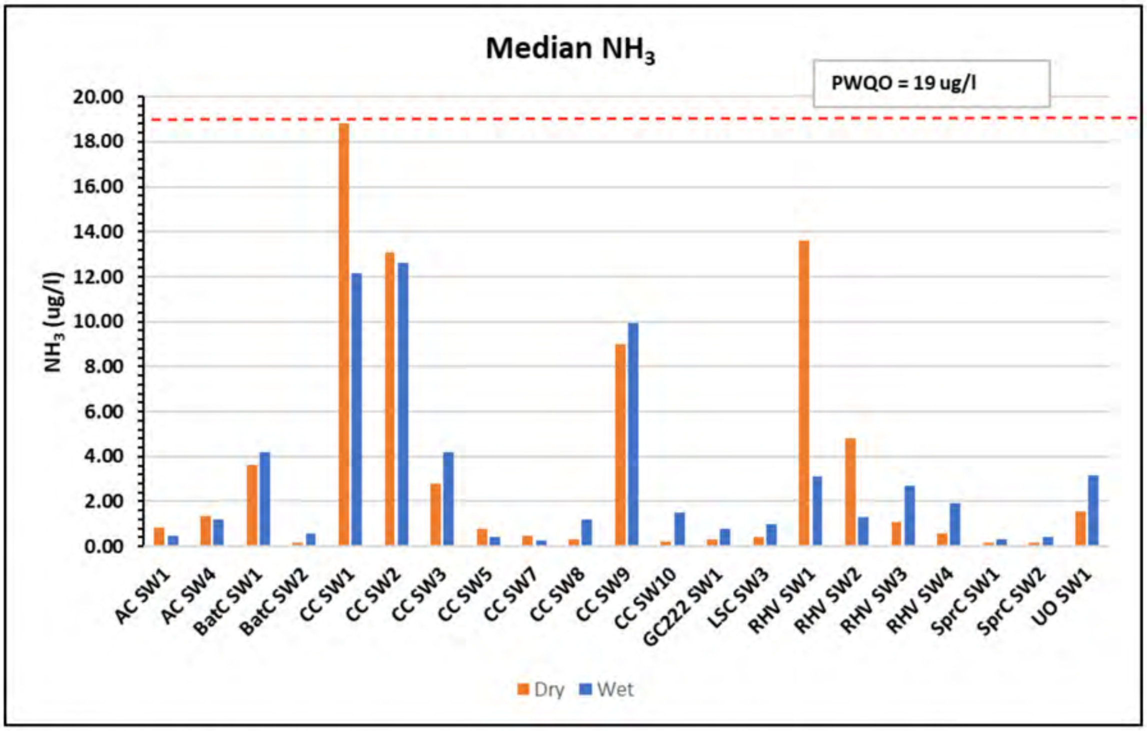

Figure 16: SWQP Dry and Wet Weather Median unionized ammonia as NH_3 concentrations

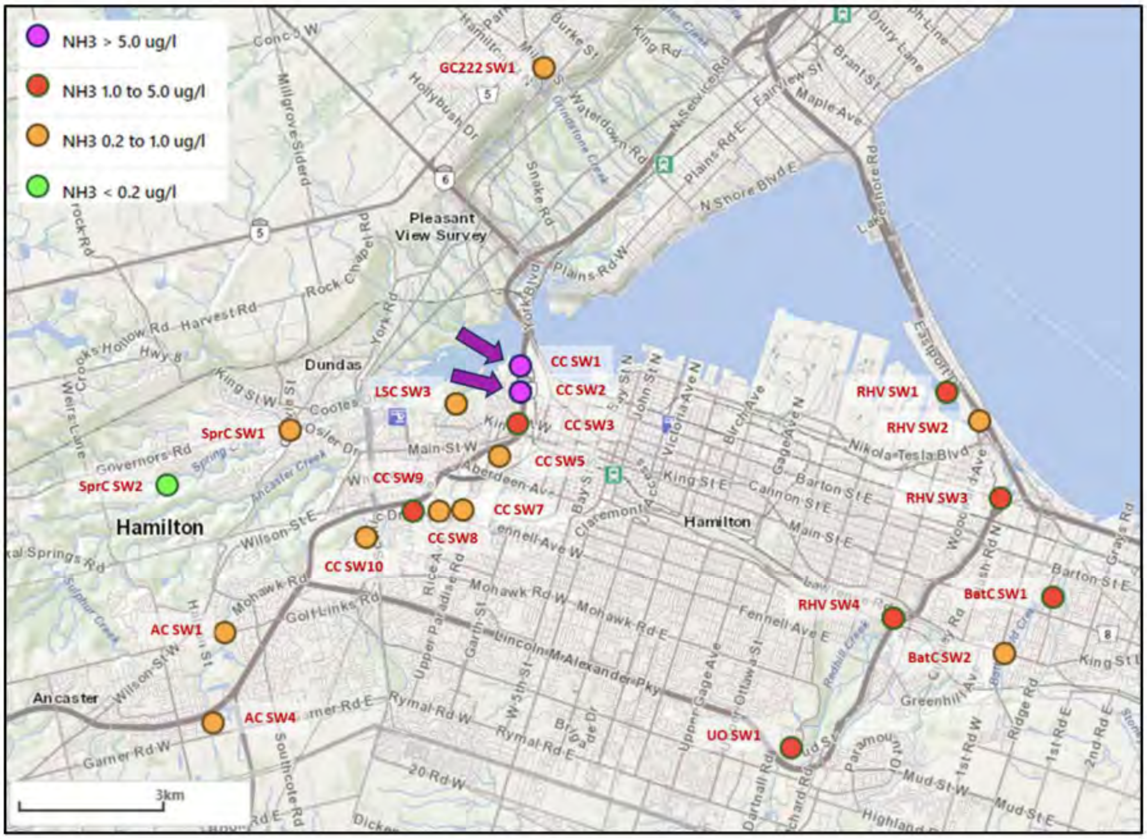

Figure 17: SWQP Wet weather 25th percentile unionized ammonia as NH_3 concentrations

Wet weather NH_3 concentrations exceeded dry weather concentrations at 13 of the 21 locations (Figure 16). They were slightly lower at five locations, and much lower at the remaining three locations (CC SW1, RHV SW1, RHV SW2). Wet weather increases would be expected as the result of urban runoff (Lee et al. 2005) and the non-parametric ANOVA and 25th percentile map (Appendix B, Figure 17) both show a more homogenous distribution of elevated concentrations at most locations that is consistent with this. This analysis also shows the lower Chedoke Creek Stations CC SW1 and CC SW2 as significantly exceeding ($p<0.05$) eight of the other locations and despite having the highest wet weather ammonia concentrations, wet weather contributions actually diluted the dry weather concentrations at these locations (as well as at the lower Red Hill Valley stations). Dry weather inputs at these locations appear to have a greater effect on tributary water quality than urban runoff.

4.2.6 Total Suspended Solids, Copper, Iron and Lead

Results for TSS were consistently low across most locations (Table 3, Table 4, Figure 18). Predictably, wet weather concentrations generally exceeded those observed during dry weather but only results for Stations CC SW1 and CC SW8 exceeded 25 mg l^{-1}. The large increase in TSS concentrations observed at CC SW8 may have been an artifact of the relatively few wet weather samples collected (4) but three of the four observations substantially exceeded 100 mg l^{-1} so the increase was not driven by a single anomalous event and there may be a local erosion source worth investigating at this location.

The pattern of variation in TSS concentrations was very similar for the metals copper, iron, and lead with strong correlations between TSS and these metals at virtually all locations (Appendix B; Figures 18, 19). The exceptions were stations in lower Chedoke Creek and Red Hill Creek (CC SW1, CC SW3 and RHV SW2) which may have been influenced by the proximity the Woodward Ave. WWTP and lower Chedoke Creek stormwater detention infrastructure. The wet weather TSS spike at CC SW8 was reflected in similar relative increases in concentrations of these metals which strongly suggests that they were associated with particulates. Roadway runoff is a well-documented source of heavy metals such as copper, iron, lead, and zinc (Grant et al. 2003; Lough et al. 2005; Apeagyei et al. 2011; Petrucci et al. 2014) so wet weather increases in these contaminants are not surprising in urban landscapes (Table 5).

Dry weather median copper concentrations remained below the PWQO of 0.0050 mg l^{-1} at all locations but varied considerably across sampling locations from less than 0.001 mg l^{-1} at Westdale Creek (LSC SW3) and the Ancaster Creek Stations (AC SW1 and AC SW4), to greater than 0.004 mg l^{-1} at the Red Hill Creek Station (RHV SW2). Wet weather copper concentrations increased at all locations (Figure 18)

Table 5: Primary sources of heavy metals in roadway runoff (from Grant et al. 2003)

Constituents	Sources
Aluminum	Natural as well as anthropogenic sources such as aluminum works industries
Cadmium	Tire wear, brake pads, combustion of oils, insecticides are also other sources
Chromium	Corrosion of welded metal plating, moving engine parts, brake lining wear
Cobalt	Wastes from tire and vehicle appliance manufacturing
Copper	Metal plating, bearing and bushing wear, moving engine parts, brake lining wear, fungicides and insecticides
Iron	Auto body rust, steel roadway structures, moving engine parts, corrosion of vehicular bodies
Lead	Leaded gasoline, tire wear
Nickel	Diesel fuel and gasoline, lubricating oil, metal plating, bushing wear, brake lining wear, asphalt paving
Zinc	Tire wear, motor oil, grease

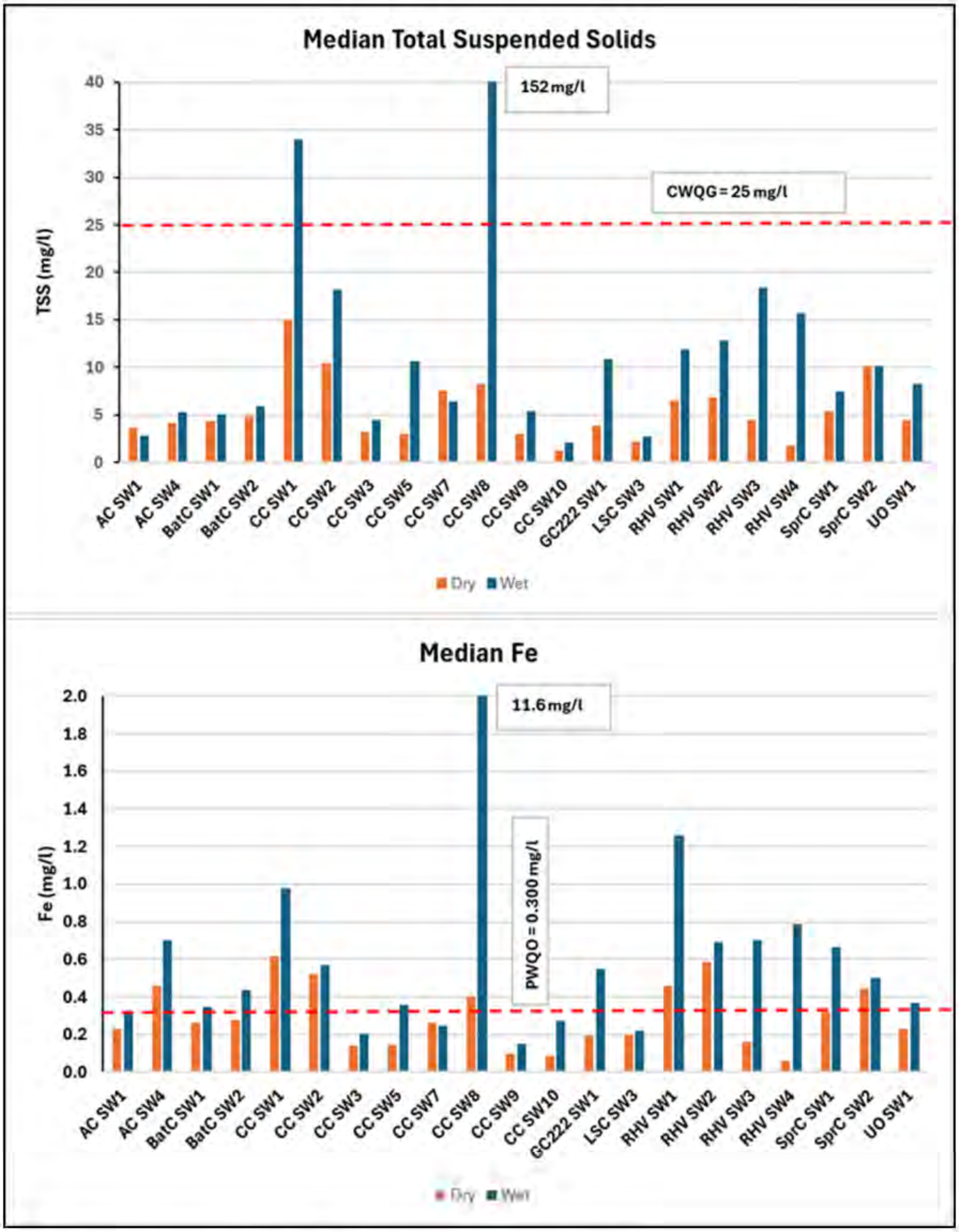

Figure 18: SWQP Dry and Wet Weather Median concentrations of TSS and Fe

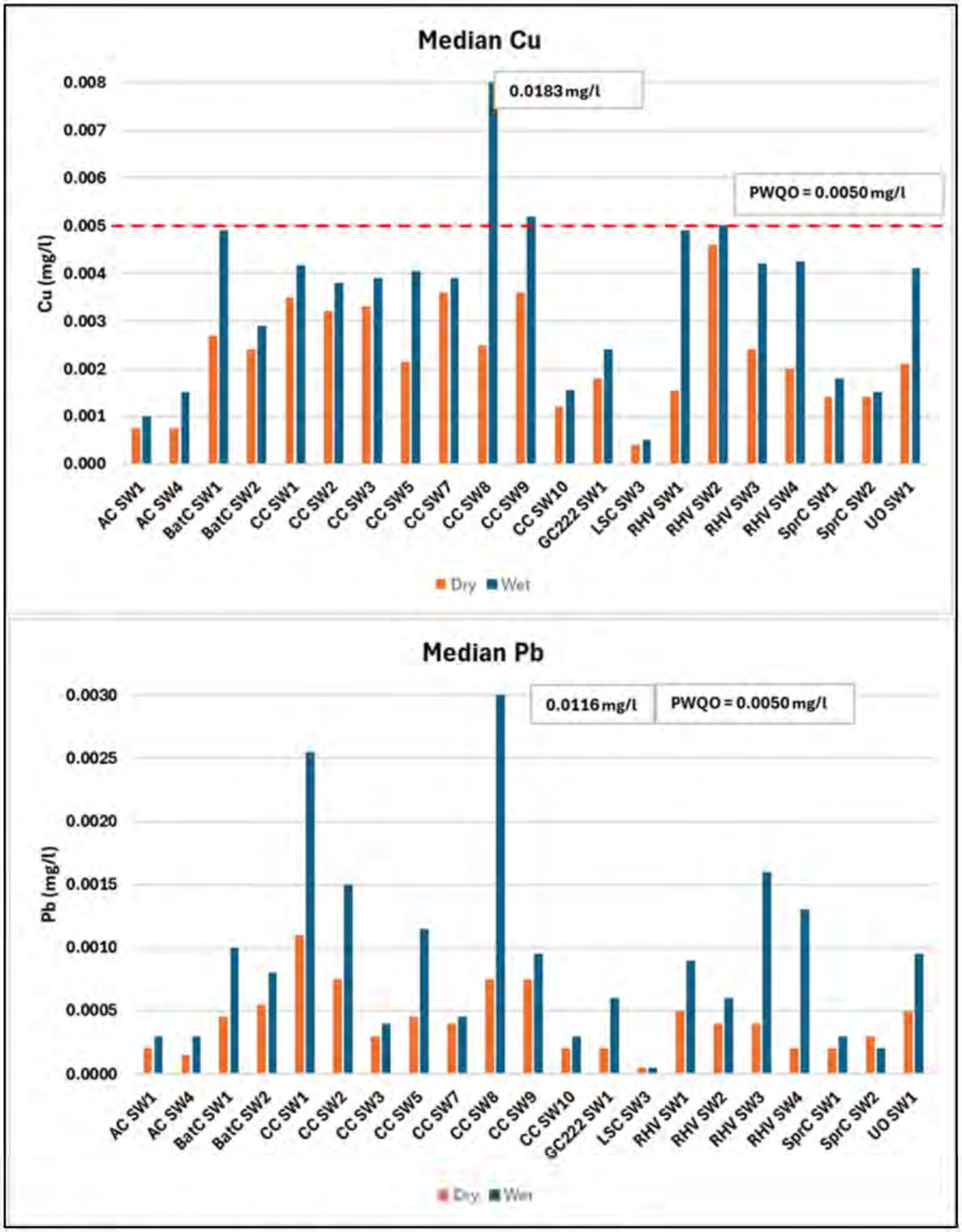

Figure 19: SWQP Dry and Wet Weather Median concentrations of Cu and Pb

which reflects its ubiquitous presence in road dust and urban stormwater. Wet weather concentrations exceeded the PWQO at only two sampling locations, so copper does not generally appear to be a problem. The concentration of 0.0183 mg l^{-1} at Station CC SW8 was more than three times higher than the next highest observation and was evidently related to the large relative increase in TSS. Management of the TSS source at this location would also reduce concentrations of metals including copper.

Dry weather median concentrations of iron ranged from 0.060 mg l^{-1} at RHV SW4 to 0.616 mg l^{-1} at CC SW1 which was one of seven sampling locations with median dry weather concentrations exceeding the PWQO of 0.300 mg l^{-1}. The increase in median wet weather concentrations at virtually all locations mirrored the increase in wet weather TSS and resulted in 15 locations with concentrations greater than the PWQO. The exception was CC SW7 which decreased very slightly for both TSS and iron and which was one of six locations that remained below the PWQO even during wet weather. The huge spike in wet weather TSS observed at CC SW8 also resulted in an extremely high iron concentration at this location (11.6 mg l^{-1}, nearly 40 times higher than the PWQO). Even though there were only four wet weather samples collected, three of them were greater than 11 mg l^{-1} which confirms that this was not an anomaly influenced by one observation.

Dry and wet weather concentrations of lead remained far below the PWQO of 0.005 mg l^{-1} but there was considerable variation in dry weather concentrations across sampling locations and wet weather concentrations were higher than dry weather. The generally low concentrations of lead reflect long term improvements resulting from its phasing out as a fuel additive and the resulting decrease in the lead content of urban dust and sediment. The strong correlation between TSS and lead at most locations (Appendix B) suggests that the observed geographical variation in wet and dry concentrations of lead is primarily a function of variation in TSS across locations.

4.2.7 Zinc

Zinc behaved differently than other metals and was poorly correlated with TSS due to dry weather anomalies (Appendix B). Thirteen locations had dry weather zinc concentrations that exceeded the interim PWQO of 0.020 mg l^{-1} so there is some evidence of a potential concern for the protection of aquatic life although zinc toxicity is primarily associated with the aqueous form and is mitigated by hardness and dissolved organic carbon (DOC). Particulate forms are generally non-toxic however (CCME 2018), so these total zinc observations do not necessarily indicate a problem.

Concentrations ranged from far below the PWQO 0f 0.020 mg l^{-1} with concentrations of 0.002 mg l^{-1} or less at the Spring Creek locations (SprC SW1, SprC SW2) and Westdale Creek (LSC SW3) to approximately 0.150 mg l^{-1} at CC SW9 and Red Hill Creek at Albion Falls (UO SW1). The non-parametric ANOVA showed these latter two locations to be significantly ($p<0.05$) greater than 15 or more of the other locations with the Spring Creek, Westdale Creek and Grindstone Creek (GC222 SW1) locations being significantly less than 10 or more locations (Appendix B). This pattern is reflected in dry weather 25th percentile map (Figure 20). Evidently dry weather sources of zinc are being detected at CC SW9 and UO SW1. Zinc is correlated with chloride and sodium at the Albion Falls location (Appendix B), which suggests that it may be in an aqueous form associated with a groundwater effect on baseflow. This is not the case at CC SW9 where it is only correlated with nitrate (Appendix B) but not obvious cross connection tracers such as TP or *E. coli*.

Wet weather concentrations were higher than dry weather at 11 locations and approximately the same at three locations (Figure 21). The largest relative increase was at CC SW8 and this was one location where there was a good correlation between TSS, zinc and other metals suggesting that the sources were similar to those for other metals and that it was in the less toxic particulate form. Wet weather concentrations were, however, less than dry weather concentrations at seven locations including six of the eight Chedoke Creek sampling stations as well as Red Hill Creek at Albion Falls (UO SW1). This wet weather dilution effect at Albion Falls was similar to that seen for chloride which suggests a dry weather baseflow contribution associated with groundwater. The six Chedoke Creek locations (CC SW1, CC SW2, CC SW3, CC SW5, CC SW7, CC SW10) where a dilution effect occurred for zinc during wet weather showed a similar pattern for nitrate (although not sufficiently similar to generate a strong correlation). As noted previously, wet weather reductions in ammonia were also seen at several of the Chedoke Creek locations but again, the similarity was not sufficient to generate a strong correlation with zinc. These anomalous wet weather concentration decreases for Zn suggest that there are dry weather sources that exert a more significant effect on water quality than the typical increases associated with urban runoff. A similar dry weather zinc anomaly was noted for Indian Creek during event-based monitoring over the period 2010 to 2012 (Long et al. 2014) so this is not unprecedented.

Figure 20: SWQP Dry Weather 25th percentile Zn concentrations

Potential sources of zinc in urban environments include electroplaters, smelting and ore processors, domestic and industrial sewage, combustion of solid wastes and fossil fuels, road surface runoff, corrosion of zinc alloy and galvanized surfaces, and tire debris (CCME 2018). It is also strongly associated with tire wear (Apeagyei et al. 2011) as well as motor oil and grease (Grant et al. 2003). It is not clear why any of these sources would lead to dry weather anomalies at certain locations, but zinc tends to strongly react with organic and inorganic compounds and forms stable combinations with many organic substances, including humic and fulvic acids and a wide range of biochemical compounds (CCME 2018) so this may be related to localized elevations in groundwater concentrations that affects baseflow. It may also be worth researching links to historic property use in these areas.

The non-parametric ANOVA for wet weather results also show CC SW9 and UO SW1 as significant outliers (P<0.05) but not to the same extent as during dry weather (Appendix B). Westdale Creek (LSC SW3) and Grindstone Creek (GC222 SW1) remained significantly less than 11 of the other locations. These patterns are illustrated in the map 25th percentile wet weather concentrations (Figure 22).

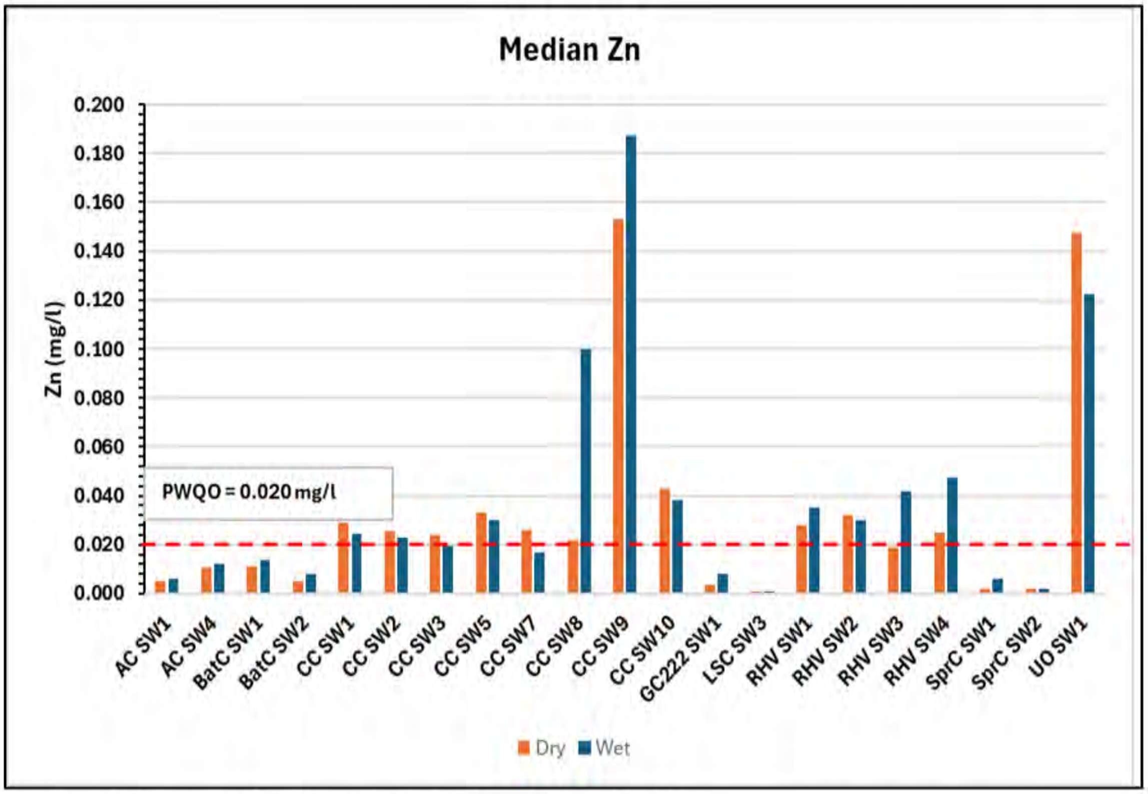

Figure 21: SWQP Dry and Wet Weather Median concentrations of Zn

Figure 22: SWQP Wet Weather 25th percentile Zn concentrations

4.3 Typical Contaminant Concentrations for Urban Watersheds

Comparison of test results with water quality guidelines and standards such as the PWQOs and CWQGs show frequent “exceedances” for chloride, total phosphorus (TP) and zinc at highly urbanized locations especially during wet weather. These guidelines and standards represent ideal conditions for the protection of sensitive aquatic life but are not particularly useful as indicators of anomalous conditions in urban landscapes. For *E. coli*, the PWQO of 200 counts/100 ml is designed for the protection of human health through exposure at bathing areas and requires the calculation of a geometric mean based on five or more samples. As such, it also does not provide a useful benchmark for flagging anomalies in urban tributaries.

Unsurprisingly, there tends to be a positive correlation between the proportion of urban land use and median contaminant concentrations although the outlier effect of the geographical anomalies that have been flagged in the previous discussion make these correlations weak (Figure 23). In order to derive dry and wet weather benchmark concentrations for all parameters of interest, the set of dry and wet weather median concentrations for all parameters at all stations (Table 3, Table 4) was modified by removing:

- a) *all results for sampling locations with less than 50% urban landcover;*
- b) *all results at “anomalous” Stations CC SW9, RHV SW1, RHV SW2;*
- c) *anomalous zinc results at Station UO SW1;*

d) *anomalous chloride results at Station LSC SW3; and*
e) *all wet weather results for Station CC SW8 (where extremely high median concentrations were observed based on only four sample results).*

The 75th percentile concentrations were then calculated for this reduced data set representative of urban sampling locations without obvious concentration anomalies. Concentrations exceeding these thresholds are in the top quartile of these typical values and can, therefore, be assessed as possible outliers.

For parameters where median concentrations exceeded the PWQOs or CWQGs (i.e. chloride*, E. coli*, TP, and zinc) suggested benchmarks for dry weather and wet weather samples were based on these 75th percentile typical concentrations (Table 6). Typical concentrations for nitrate, unionized ammonia, copper, and lead were all below PWQOs and CWQGs so no new benchmarks were proposed for these parameters. Applying these benchmarks to SWQP results for chloride, *E. coli*, TP, and zinc at all stations flags the same stations highlighted by the non-parametric ANOVA which suggests that they are reasonable and robust when applied to individual observations (Table 6).

The results suggest that depending on the substance, there were four to seven locations where more than 50% of the sampling results for chloride, E. coli, TP, or zinc exceeded these proposed benchmarks and where additional attention to source control may be warranted. Conversely, there were 14 to 17 locations where less than 50% of sampling results exceeded these benchmarks and where additional effort to locate and manage sources would not appear to be a high priority (Table 6).

Sources of chloride are likely associated with winter de-icing programs and consequently the most realistic source control option is to maintain ongoing salt management efforts. Dry weather sources of *E. coli* and TP, on the other hand, are potentially linked to sanitary sewage and would appear to warrant additional efforts to identify cross connections. Wet weather sources of these substances are ubiquitous in urban landscapes so the most effective approach to achieving additional wet weather reductions would be associated with ongoing stormwater management initiatives.

These same initiatives would also help address wet weather sources of zinc, but the dry weather anomalies noted at CC SW9, CC SW10, and UO SW1 represent more of a challenge since the sources are not yet well understood.

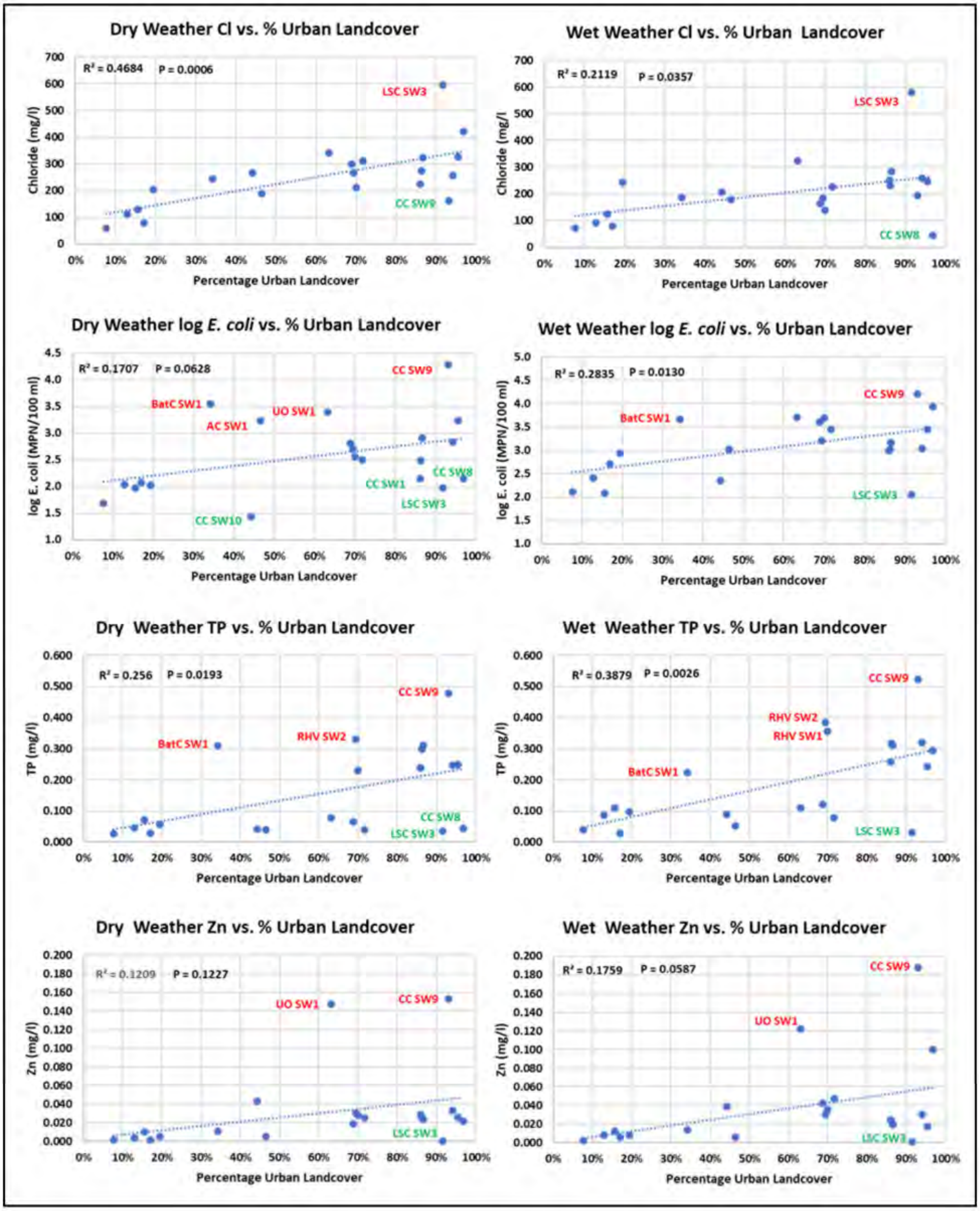

Figure 23: SWQP Chloride, E. coli*, TP, and Zn concentrations versus percentage urban landcover*

Table 6: Proportion of SWQP samples exceeding proposed benchmarks

	Suggested benchmarks	*300*	*1000*	*0.250*	*0.030*
Station Location	***Total No. of samples***	**Cl (mg/l)**	**E. coli (MPN/100ml)**	**TP (mg/l)**	**Zn (mg/l)**
AC SW1	21	5%	52%	62%	0%
AC SW4	21	10%	5%	0%	0%
BatC SW1	31	16%	87%	48%	19%
BatC SW2	29	31%	34%	3%	10%
CC SW1	30	30%	33%	50%	40%
CC SW2	31	32%	39%	58%	35%
CC SW3	31	58%	48%	81%	29%
CC SW5	34	29%	50%	59%	56%
CC SW7	31	0%	74%	48%	26%
CC SW8	16	63%	31%	19%	50%
CC SW9	30	17%	97%	93%	100%
CC SW10	31	35%	6%	6%	77%
GC222 SW1	21	0%	24%	0%	0%
LSC SW3	23	100%	9%	0%	0%
RHV SW1	27	7%	48%	59%	44%
RHV SW2	32	13%	53%	69%	47%
RHV SW3	32	44%	59%	3%	50%
RHV SW4	32	50%	47%	0%	56%
SprC SW1	21	0%	19%	0%	0%
SprC SW2	21	0%	5%	0%	0%
UO SW1	34	71%	88%	3%	100%

4.4 SWQP Summary

The spatially intensive, and event-based data generated by SWQP monitoring not only demonstrated water quality patterns associated with upstream land use, but dry weather results also flagged potential “hot spots” for *E. coli* and TP associated with potentially manageable sources such as cross connected sanitary and storm sewers.

Parameters such as chloride, nitrate, ammonia, and zinc showed wet weather dilution effects at several stations indicating that there are watershed locations where the dry weather influence of elevated groundwater concentrations exceeds the influence of storm water runoff during wet weather events. Management options to address this phenomenon are limited since degraded groundwater quality will reflect historical inputs associated with urban land use, however programs such as road salt management for winter road de-icing will help over the long term.

Comparing SWQP results with water quality guidelines, standards and benchmarks suggests that for *E. coli*, management efforts can initially be focused at two high priority harbour watershed locations (CC SW9: Chedoke Creek Mountview Falls at Railtrail Bridge; and UO SW1: Red Hill Creek at Albion Falls) as well as at the Battlefield Creek location BatC SW1 outside the harbour watershed. High priority locations for management of TP could initially be concentrated at the same Chedoke Creek location as well as at CC SW3 (Chedoke Creek at Glen Rd. Outfall).

Taken together, SWQP monitoring results suggests that initial follow up efforts associated with identifying and managing anomalous sources of *E. coli* and TP can be concentrated at a small subset of program monitoring locations. It also suggests that there are four locations (AC SW4: Ancaster Creek near Maple Lane Park; GC222 SW1: Grindstone Creek at Mill Street South; SprC SW1: Spring Creek West of Ogilvie Street; and SprC SW2: Spring Creek at John White Trail Bridge) where water quality results are consistently good and where further intensive monitoring may no longer be needed if it becomes desirable to redeploy resources to more problematic areas. These locations are all predominantly agricultural or natural and have less than 20% upstream urban land use.

Finally, SWQP results also reinforced the previous findings from the MECP tributary loadings study monitoring over the period 2010 to 2012 (Long et al. 2014a, 2014b, HHRAP 2018) which showed anomalous dry weather zinc concentrations particularly in Indian Creek on the Halton side of the harbour. Three harbour watershed locations showed particularly persistent and elevated zinc concentrations. Two of these were also associated with anomalous *E. coli* results (Stations CC SW9 and UO SW1) while the third (Station CC SW10: Chedoke Creek at Outfall near 130 Daffodil Crescent) was not associated with any other contaminant issues.

These findings suggest that it may be appropriate to further investigate sources of zinc and the potential toxic effects of chronic zinc exposure on aquatic organisms. The potentially toxic influence of groundwater contaminants, including metals such as zinc, on baseflow water quality has been flagged as a potentially overlooked contributor to “urban stream syndrome” (Roy and Bickerton 2012) and the dry weather anomalies are suggestive of a groundwater influence on baseflow zinc concentrations. It is reasonable to infer that the dissolved phase accounts for a significant proportion of total zinc and the CWQG chronic exposure threshold[8] of 0.007 mg l^{-1} for dissolved zinc is well below the interim PWQO of 0.020 mg l^{-1} (total zinc). Furthermore, observed concentrations at two locations (CC SW9 and UO SW1) persistently exceeded the CWQG acute exposure threshold of 0.037 mg l^{-1} for dissolved zinc which may suggest that zinc is the most significant metal exerting toxic effects on aquatic life in some regions of the heavily urbanized watersheds. Allocation of additional resources to identifying manageable sources near high priority locations may be warranted presuming that toxic effects can be confirmed since this is not always the case given the mitigating influences of hardness, pH, and dissolved organic carbon (DOC) (Popick et al. 2022).

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[8] *Illustrative value for surface water of 50 mg CaCO3·l^{-1} hardness, pH of 7.5 and 0.5 mg·l^{-1} DOC*

5. HAMILTON CONSERVATION AUTHORITY COOTES TRIBUTARY MONITORING DATA ANALYSIS

The Hamilton Conservation Authority (HCA) started collecting water quality samples in support of the Remedial Action Plan (RAP) program for the Hamilton Harbour Area of Concern at some stations in 2014 and expanded this to 11 stations in 2018. This sampling effort emphasizes high frequency (typically bi-weekly) monitoring at tributary stations in the Chedoke Creek, Ancaster Creek, and Borer's Creek watershed (Table 1, Figure 24). Sample analysis for this ongoing program is undertaken at the City of Hamilton Environmental Laboratory and includes analysis for total suspended solids, loss on ignition, ammonia/ammonium (as N), total phosphorus (TP), total dissolved phosphorus, and *Escherichia coli* (*E. coli*).

Figure 24: Hamilton Conservation Authority and Royal Botanical Gardens Cootes/Grindstone tributary monitoring

The following analysis used available data collected during the period 2021 through 2023 to allow comparison with City of Hamilton SWQP results. Data were prepared for analysis by separating "wet" and "dry" weather results using the same criterion as the SWQP data analysis (≥ 4mm of recorded precipitation within a 24-hour period prior to and during the sampling date). The distribution of wet and dry data for each location was assessed using the Shapiro-Wilk normality test and the results showed non-normal (typically right-skewed) distributions for most parameters at all locations so, as with the SWQP results, data were summarized and analyzed using rank-based non-parametric statistics (medians, quartiles, Kruskal-Wallis ANOVA).

5.1 HCA Multivariate Analysis

Median dry and wet weather results are shown in Tables 7 and 8 and these results were used to undertake Principal Component Analysis (PCA) and Hierarchical Clustering (HC). Inspection of these results shows a marked difference between water quality in Chedoke Creek and other locations (Ancaster Creek, Spencer Creek and Borer’s Creek). The dry weather PCA biplot (Figure 25) and HC dendogram (Figure 26) clearly illustrate this. Wet weather results were slightly more homogeneous, but Stations CC-11 and CC-9 emerged as widely separated from most other locations. Total ammonia/ammonium was the factor most responsible for separating CP-11 while CC-9 was separated by E. coli, nitrate and TP. These are not surprising results given the relatively natural land use associated with Ancaster Creek compared with the highly urbanized condition in Chedoke Creek (Table 1), but the contrast is very striking.

Table 7: Dry weather median concentrations at Hamilton Conservation Authority stations

Station Location	N	Ammonia + Ammonium as N mg/L	E. coli MPN/100mL	Nitrate as N mg/L	o-Phosphate as P mg/L	Total Phosphorus mg/L	Total Suspended Solids mg/L	Volatile Suspended Solids mg/L
AC-1	51	**0.02**	**172**	**0.48**		**0.020**	**4.2**	**1.7**
AC-2	51	**0.01**	**140**	**0.38**		**0.017**	**5.8**	**1.6**
AC-3	50	**0.01**	**160**	**0.66**		**0.025**	**4.4**	**1.6**
AC-5	51	**0.02**	**780**	**1.04**		**0.031**	**3.6**	**2.2**
CC-3	50	**0.02**	**825**	**2.83**	**0.255**	**0.268**	**7.3**	**2.5**
CC-5	42	**0.02**	**1275**	**2.46**	**0.260**	**0.318**	**12.4**	**3.3**
CC-7	47	**0.08**	**3450**	**1.81**	**0.140**	**0.158**	**4.7**	**1.8**
CC-9	51	**0.02**	**1560**	**3.44**	**0.490**	**0.521**	**7.0**	**2.1**
CP-11	46	**0.39**	**615**	**1.98**	**0.185**	**0.314**	**12.1**	**3.2**
CP-18	48	**0.02**	**161**	**0.44**		**0.045**	**3.0**	**1.6**
CP-7	48	**0.02**	**238**	**0.56**		**0.034**	**4.6**	**2.0**
Objectives/ Guidelines	***PWQO***	***--***	***200****	***--***	***--***	***0.030***	***--***	***--***
	CWQG	***>0.28 variable***	***--***	***3.00***	***--***	***--***	***25.0***	***--***

Table8: Wet weather median concentrations at Hamilton Conservation Authority stations

Station Location	N	Ammonia + Ammonium as N mg/L	E. coli MPN/100mL	Nitrate as N mg/L	o-Phosphate as P mg/L	Total Phosphorus mg/L	Total Suspended Solids mg/L	Volatile Suspended Solids mg/L
AC-1	25	**0.03**	**361**	**0.51**		**0.043**	**14.5**	**3.0**
AC-2	22	**0.02**	**297**	**0.41**		**0.037**	**20.8**	**2.75**
AC-3	23	**0.02**	**193**	**0.67**		**0.046**	**18.8**	**2.2**
AC-5	26	**0.03**	**1080**	**0.97**		**0.051**	**9.6**	**3.7**
CC-3	23	**0.02**	**710**	**2.59**	**0.190**	**0.243**	**12.5**	**4.0**
CC-5	22/24*	**0.02**	**1275***	**2.04**	**0.185**	**0.257***	**8.0**	**2.6**
CC-7	23	**0.09**	**2500**	**1.62**	**0.080**	**0.156**	**7.2**	**2.6**
CC-9	23	**0.09**	**12200**	**3.19**	**0.330**	**0.372**	**14.2**	**3.2**
CP-11	23	**0.32**	**1400**	**1.64**	**0.150**	**0.254**	**20.9**	**5.5**
CP-18	21	**0.02**	**200**	**0.50**		**0.062**	**7.6**	**2.2**
CP-7	21	**0.04**	**261**	**0.65**		**0.070**	**21.6**	**4.2**
Objectives/ Guidelines	***PWQO***	***--***	***200****	***--***	***--***	***0.030***	***--***	***--***
	CWQG	***>0.28 variable***	***--***	***3.00***	***--***	***--***	***25.0***	***--***

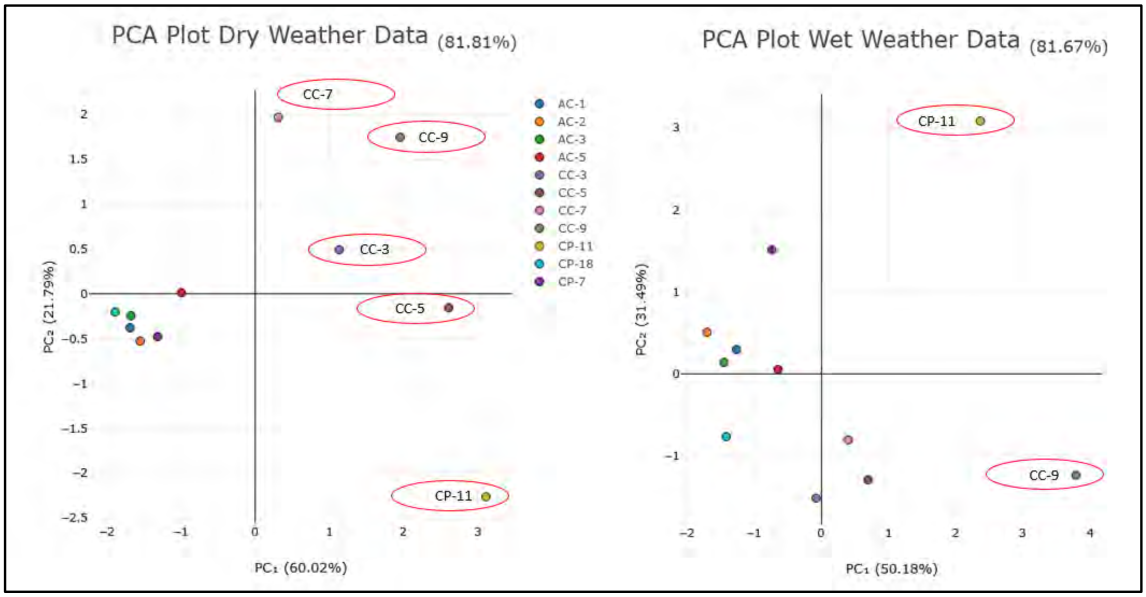

Figure 25: Hamilton Conservation Authority (HCA) Stations Principal Component Biplot Scores (PC_1 vs. PC_2)

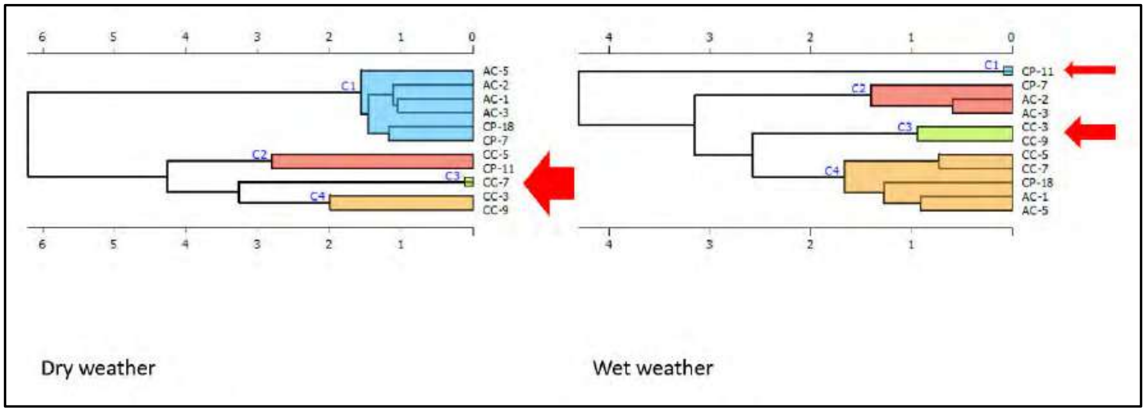

Figure 26: HCA Stations Hierarchical Clustering Dendrogram (Top 4 clusters, Euclidean Distance, Ward's linkage)

5.2 HCA Univariate Analysis

5.2.1 *E. coli*

Dry weather median *E. coli* results ranged from a low of 140 MPN/100ml at Ancaster Creek Station AC-2 to a maximum of 3,450 MPN/100 ml at Chedoke Creek Station CC-7. Four of the locations had median counts below 200 MPN/100 ml, confirming an absence of dry weather inputs. Comparison of dry weather *E. coli* results using a non-parametric ANOVA on $\log_{10}$ transformed data flagged CC-7 as an anomaly significantly greater ($p<0.05$) than eight of the other 10 sites (Appendix C). Although this was a relative anomaly, the counts were not high enough to be persuasively indicative of a sewage related source. Counts were far less than for the anomalies observed in the SWQP data, they were not significantly greater than CC-5 or CC-9, and they were not correlated with TP or other nutrients.

This anomaly is well illustrated by the 25th percentile dry weather count map (Figure 27). Although CC-7 is the most significant anomaly, the ANOVA flagged the other locations with greater than typical dry weather counts which generally correspond to the locations (CC-5, CC-9, AC-5) flagged in the 25th percentile map. The elevated count at Ancaster Creek Station AC-5 is attributable to this location having a much higher proportion of urban and agricultural land use than other Ancaster Creek locations (Table 1).

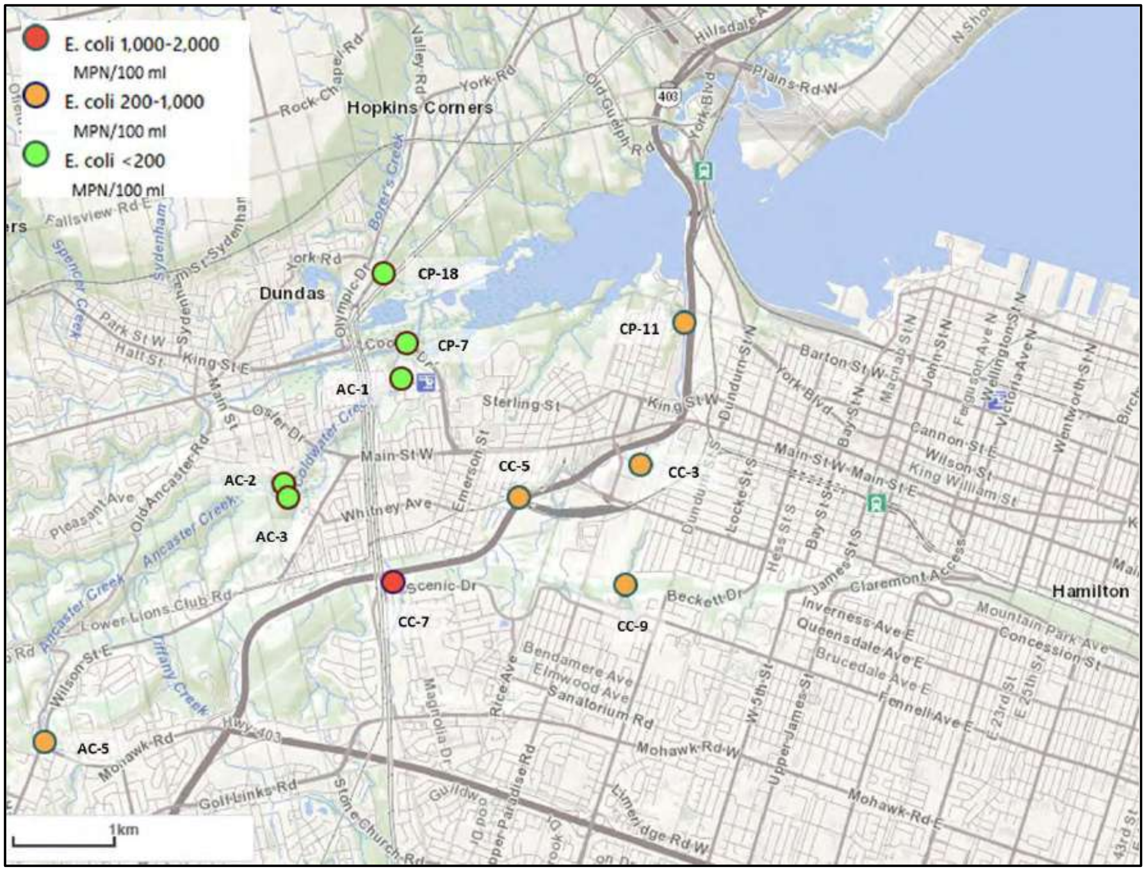

Figure 27: HCA Stations Dry weather 25th percentile E. coli *counts*

Wet weather median E. coli counts were higher at most sampling locations, reflecting the effect of urban runoff generating more degraded conditions across all locations (Table 8; Figure 28). The exceptions were at Station CC-7 where the median wet count dropped from 3450 to 2500 MPN/100ml and at Station CC-5 where it remained at 1275 MPN/100ml. Despite the similar median, the range of wet weather counts at CC-5 was much greater than during dry weather however, with four observations greater than 10000 MPN/100ml and a maximum of over 80000 MNP/100ml. The non-parametric ANOVA showed Stations CC-7 and CC-9 having significantly greater ($p<0.05$) counts than five of the other ten locations and the 25th percentile map (Figure 28) shows these anomalies.

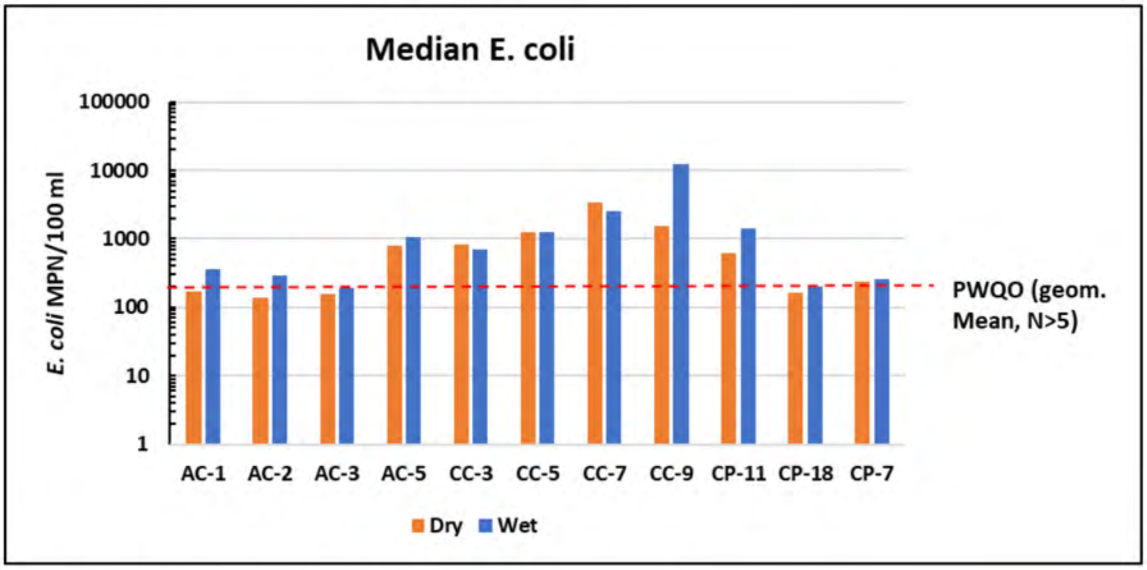

Figure 28: HCA Stations Dry and Wet Weather Median E. Coli *counts*

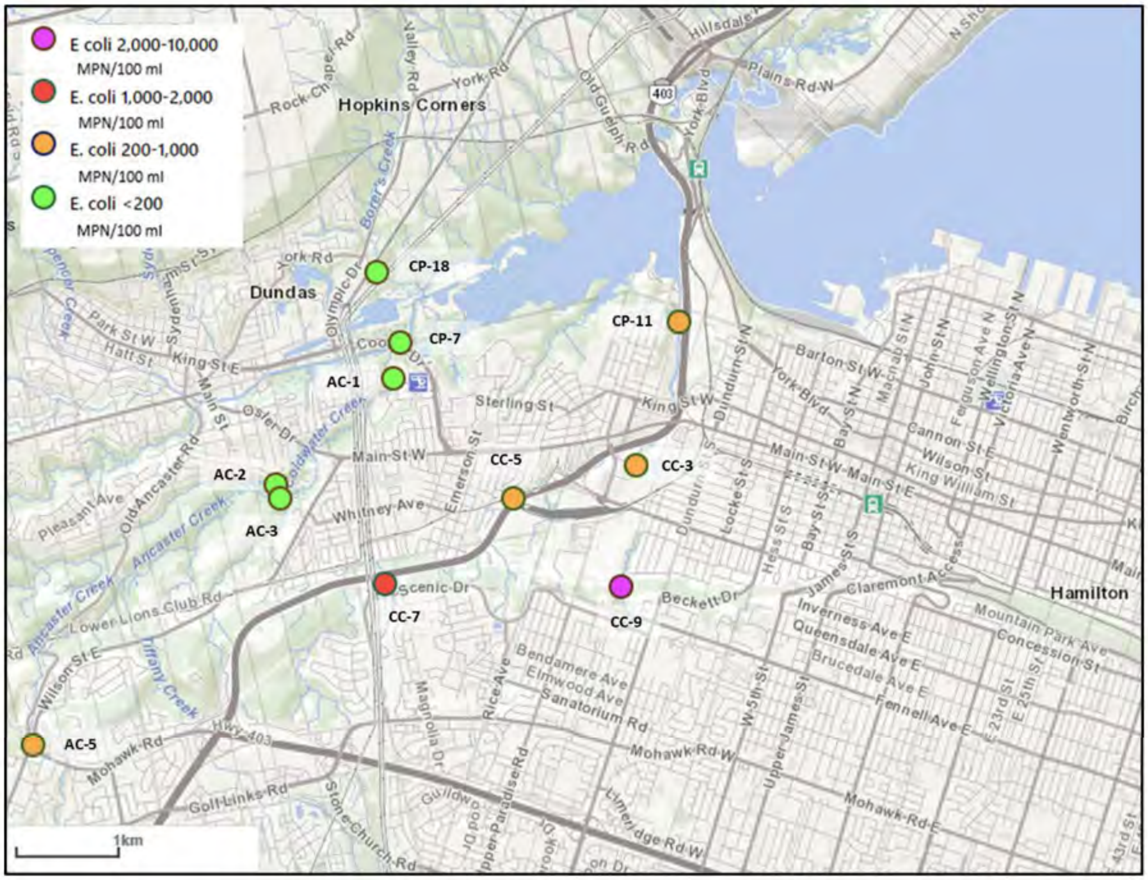

Figure 29: HCA Stations Wet weather 25th percentile E. coli *counts*

5.2.2 Total Phosphorus

Dry weather median TP concentrations varied from less than the PWQO of 0.030 mg l^{-1} at the relatively natural Ancaster Creek locations (AC-1, AC-2, AC-3), to more than 0.300 mg l^{-1} at three of the Chedoke Creek locations (CC-5, CC-9, CP-11) with a maximum of 0.521 mg l^{-1} at Station CC-9 (Table 7). The non-parametric ANOVA for dry weather TP shows the five Chedoke Creek Stations as having concentrations significantly greater ($p<0.05$) than the Ancaster Creek, Spencer Creek and Borer's Creek sampling locations. This pattern is well illustrated by the map of dry weather 25th percentile concentrations which also flags the Chedoke Creek maximum at CC-9 (Figure 30).

Figure 30: HCA Stations Dry weather 25th percentile TP concentrations

Dry weather median concentrations of greater than 0.300 mg l^{-1} at Chedoke Creek stations were strongly indicative of a dry weather source and although TP concentrations were not consistently correlated with *E. coli* or nitrate (Appendix C), *E. coli* counts and nitrate concentrations were elevated at Stations CC-5, CC-7, and CC-9. This provides some evidence that a sewage-related source may be involved. At Chedoke Creek Stations, where o-Phosphate as P data were also available, results show that TP concentrations were predominantly in the form of soluble P so these elevated dry weather concentrations appear to be associated with phosphate enriched groundwater contributing to elevated baseflow concentrations.

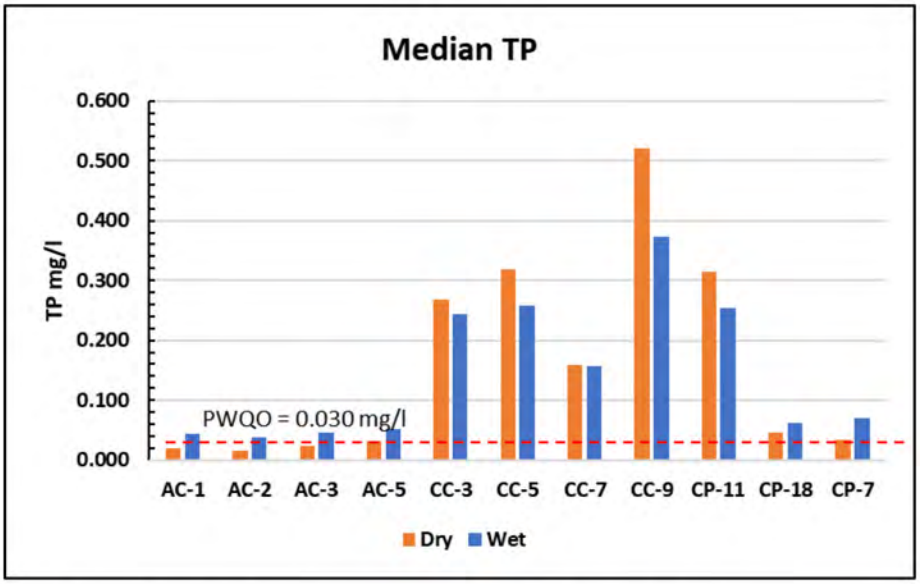

Figure 31: HCA Stations Dry and Wet Weather Median TP concentrations

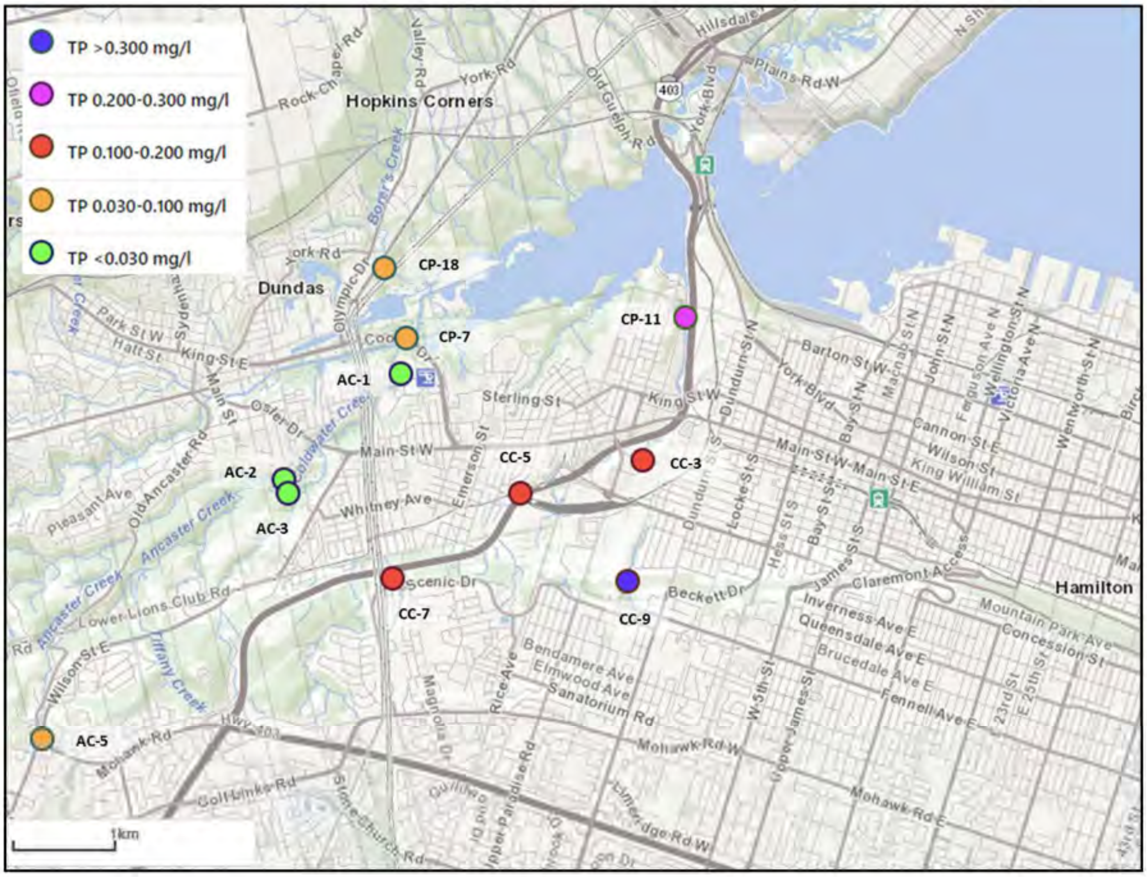

Figure 32: HCA Stations Wet weather 25th percentile TP concentrations

Wet weather median TP concentrations were greater than during dry weather at Ancaster Creek locations (Table 8, Figure 31) where they were well correlated with TSS and reflected typical wet weather increases associated with urban runoff. A dilution effect was apparent at the Chedoke Creek Stations however, with median wet weather concentrations of TP lower than during dry weather (Figure 31). There were no consistent correlations with TSS and soluble P still accounted for more than 60% of TP at these locations, so evidently the dry weather inputs of soluble P were having a greater influence on TP concentrations in Chedoke Creek than wet weather inputs associated with urban runoff which were diluting dry weather concentrations. The non-parametric ANOVA showed a similar pattern during wet weather as dry weather except for CC-7 which was no longer significantly greater ($p<0.05$) than all Ancaster Creek locations. The 25th percentile map shows this generally similar spatial pattern with Station CC-9 still showing as the greatest anomaly (Figure 32).

5.2.3 Ammonia + Ammonium, Nitrate, Total Suspended Solids, Loss on Ignition

Dry and wet weather concentrations of total ammonia, nitrate, and total suspended solids (TSS) were generally all below their corresponding CWQG values although total ammonia and nitrate concentrations were markedly higher at Chedoke Creek locations (Figures 32 to 35). Wet weather total ammonia concentrations were slightly higher than during dry weather at seven locations, similar at three locations, and lower at Chedoke Creek Station CP-11 which exhibited the highest concentrations in both dry and wet conditions (Figure 32). Ammonia is highly soluble in water so the dry weather spike at Chedoke Creek Station CP-11 would appear to be associated with ammonia enriched groundwater. As noted in the SWQP discussion, this may be related to the closed landfill at Kay Drage Park or possibly associated with vehicular inputs from the nearby Highway 403.

Nitrate concentrations were below the CWQG of 3.0 mg l^{-1} at all locations except CC-9 (Figure 33). Wet weather concentrations slightly increased at five locations in Ancaster Creek and Borer’s Creek but were lower at all Chedoke Creek locations. This dilution effect suggests that dry weather baseflow is influenced by groundwater where nitrate tends to accumulate because of its high stability and solubility.

Unlike nutrients and *E. coli*, total suspended solids (TSS) and loss-on-ignition (LOI) data did not show Chedoke Creek as distinct from more natural locations (Figures 34, 35). Wet weather concentrations were elevated at all locations which is consistent with the influence of urban runoff. The LOI results showed that the organic (i.e. combustible) fraction of TSS ranged from about 25% to 50 % during dry weather and 14% to 35% during wet weather. This is consistent with urban runoff increasing the relative contribution of inorganic particulate matter.

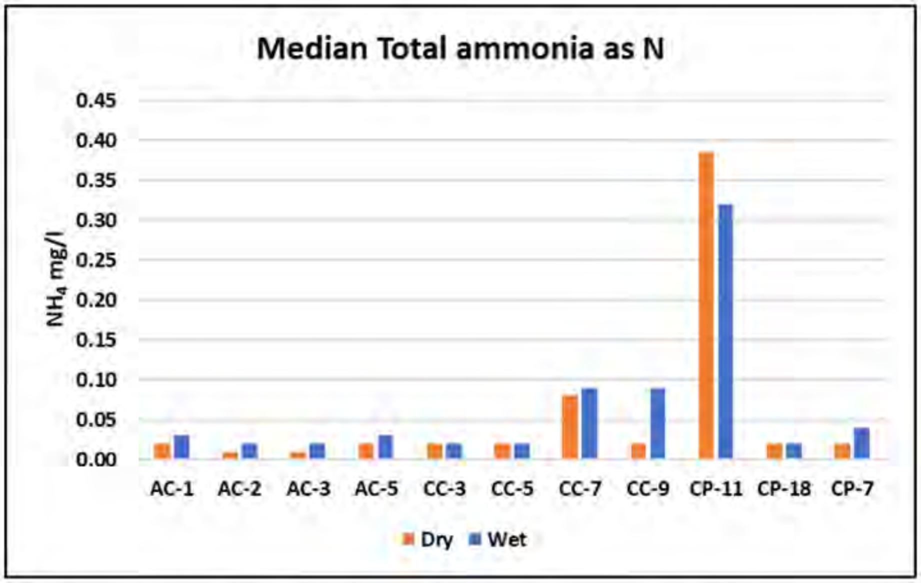

Figure 32: HCA Stations Dry and Wet Weather Median ammonia concentrations

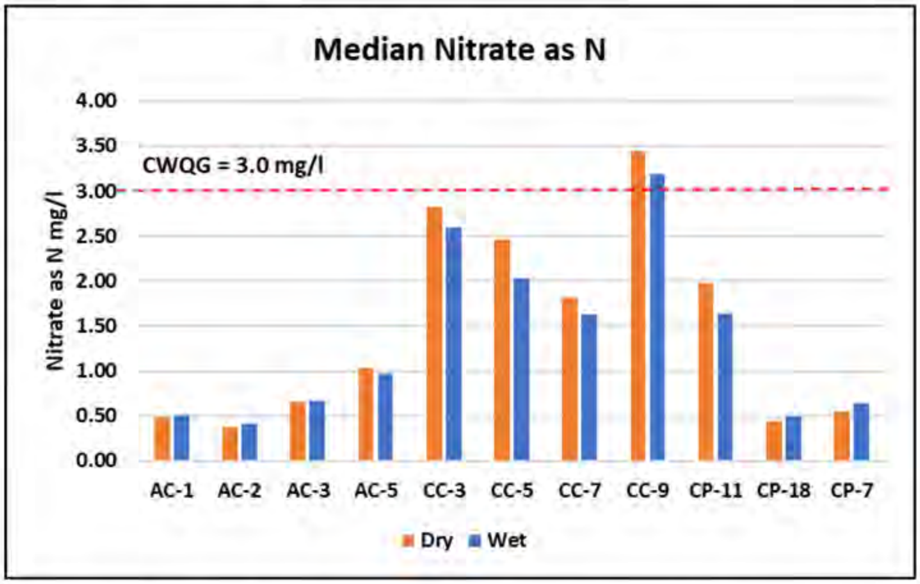

Figure 33: HCA Stations Dry and Wet Weather Median nitrate concentrations

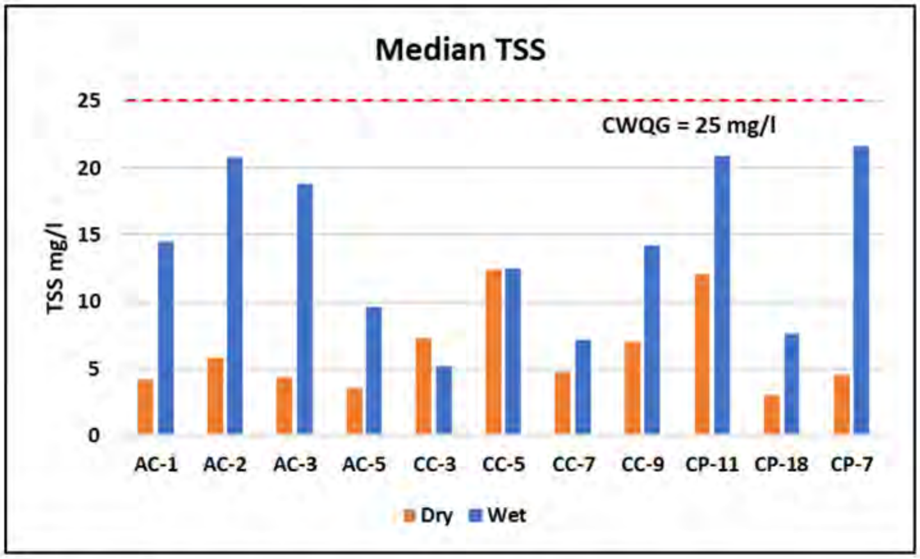

Figure 34: HCA Stations Dry and Wet Weather Median TSS concentrations

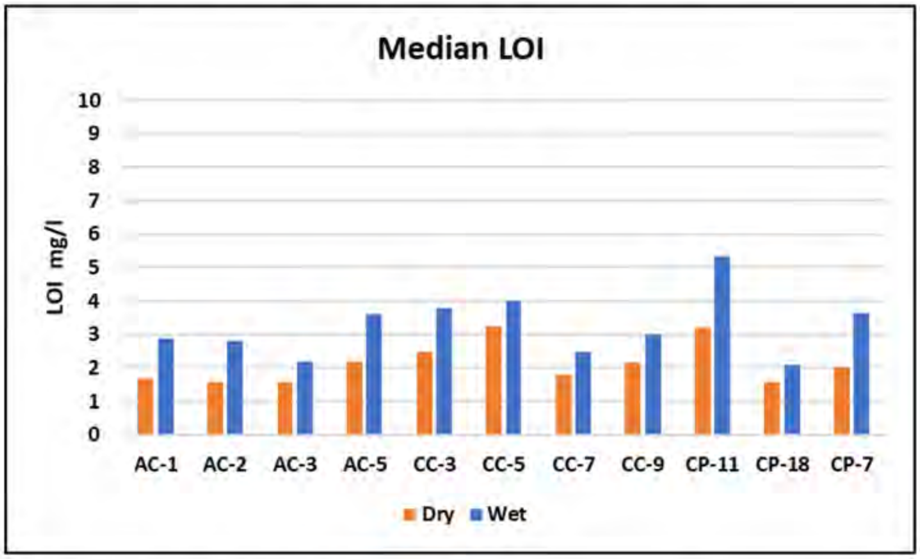

Figure 35: HCA Stations Dry and Wet Weather Median LOI concentrations

5.3 HCA Cootes Tributary Monitoring Summary

HCA data showed a marked difference between water quality at highly urban Chedoke Creek locations compared with the less urban locations in Ancaster Creek, Spencer Creek and Borer's Creek. Dry weather sampling showed anomalies within the Chedoke watershed for both *E. coli* and TP with TP concentrations predominantly in the form of soluble P suggesting that elevated dry weather concentrations are associated with phosphate enriched groundwater contributing to elevated baseflow concentrations. The greatest TP anomaly was at Station CC-9 (Chedoke Creek downstream of Middle Chedoke Falls) with the greatest *E. coli* outlier occurring at CC-7 (Chedoke Creek upstream of Upper Princess Falls).

Although dry and wet weather concentrations of total ammonia, nitrate, and TSS were generally below CWQG values, total ammonia and nitrate concentrations were markedly higher at Chedoke Creek locations (Figure 32 and 33). A wet weather dilution effect was observed for total ammonia at Chedoke Creek Station CP-11 (Chedoke Creek downstream of Kay Drage Park Bridge) and for nitrate at all Chedoke Creek locations. This dilution effect suggests that dry weather baseflow is influenced by groundwater where nitrate tends to accumulate because of its high stability and solubility.

Sampling results also showed consistently good water quality, during dry and wet weather, at the three lower Ancaster Creek locations (AC-1, AC-2, and AC-3), Spencer Creek (CP-7) and Borer's Creek (CP-18). If additional resources are required to investigate anomalies, it may be possible to reduce the bi-weekly sampling effort at these locations.

6. HAMILTON CONSERVATION AUTHORITY PWQMN MONITORING DATA ANALYSIS

Since 2002 the Hamilton Conservation Authority (HCA) has also contributed to the Provincial Water Quality Monitoring Network (PWQMN) in partnership with the provincial government. Samples were collected at approximately monthly intervals during the ice-free season at five locations with data being available for 2021 and 2022 (Table 1, Figure 36).

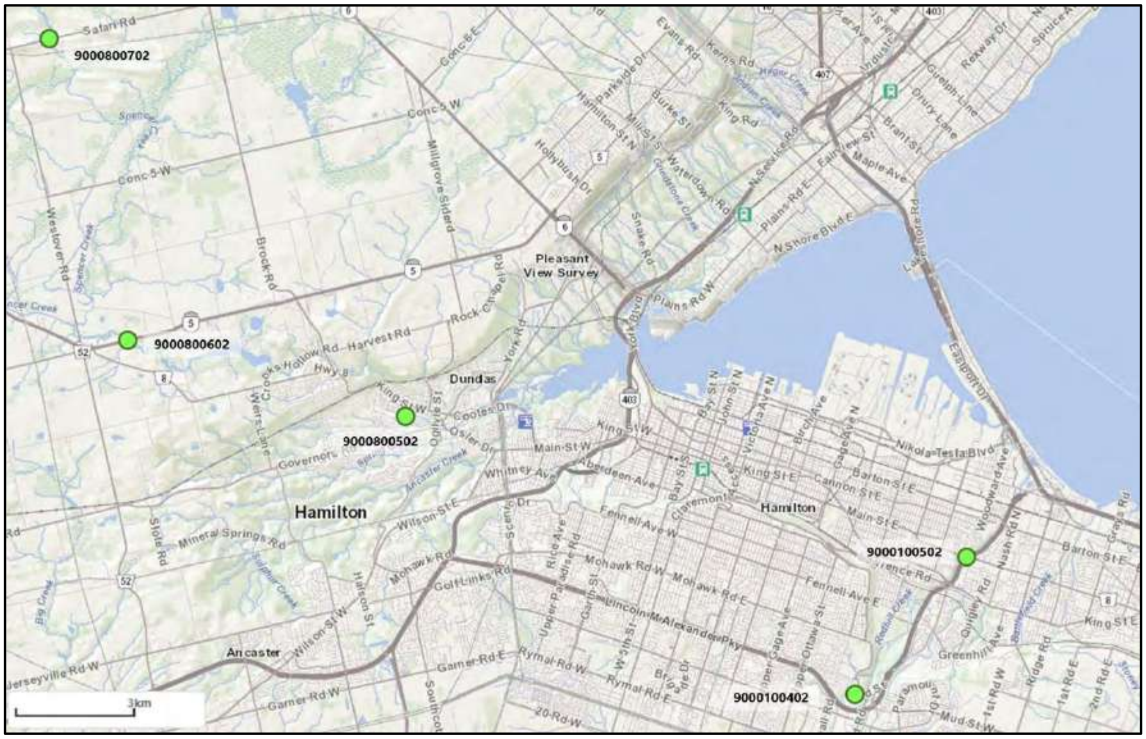

Figure 36: Hamilton Conservation Authority (HCA) PWQMN Monitoring Stations

Samples were collected by HCA and analyzed by the Ministry of Environment, Conservation and Parks (MECP) laboratory for nutrients, total suspended solids (TSS) and metals as well as field-based measurements for various physical parameters such as temperature, pH, and conductivity (see Appendix A for complete list). The PWQMN sampling protocol is not event based and consequently tends to be heavily weighted to sampling during dry weather. In this case, only three of the 16 samples collected in 2021 and 2022 were obtained during wet weather.

The data were screened to reduce the number of parameters in a similar fashion to the City of Hamilton SWQP data. Results with a preponderance of results below detection were not analyzed. Tables 9 and 10 summarize dry weather and wet weather results for parameters with water quality guidelines or standards (PWQO or CWQG).

6.1 PWQO Multivariate Analysis

The small sample size for wet weather results precluded statistical analysis, however dry weather data (Table 9) were analyzed using PCA and hierarchical clustering (HC). The PCA showed the upstream

Spencer Creek and Red Hill Creek Albion Falls results separated from other station results and each other. These locations were also identified as separate clusters in the HC dendogram (Figure 37). Iron

Table 9: Dry weather median concentrations at PWQMN stations

Station ID	Station Location	N	Cl (mg/l)	Total Ammonia as NH3 (mg/l)	Nitrate (mg/l)	Phosphate (mg/L)	TP (mg/L)	TSS (mg/l)	Cu (mg/l)	Fe (mg/l)	Zn (mg/l)
9000100402	Redhill Creek, Albion Falls	13	403	0.050	1.17	0.056	0.086	5.6	0.0041	0.126	0.130
9000100502	Redhill Creek, Queenston Rd	13	366	0.040	0.61	0.024	0.042	3.5	0.0035	0.075	0.018
9000800502	Spencer Creek, Market St.	13	100	0.030	0.72	0.019	0.029	6.0	0.0018	0.112	0.020
9000800602	Spencer Creek, Hwy 5	12*/13	62	0.044	0.29*	0.025	0.061	3.8*	0.0010*	0.206	0.012
9000800702	Spencer Creek, Safari Rd.	10*/12**/13	60	0.050	0.11**	0.011	0.025	2.9**	0.0007*	0.150	0.016
Objectives/Guidelines		*PWQO*					*0.030*		*0.0050*	*0.300*	*0.020*
		CWQG	*120*	*>0.28 variable*	*3.00*			*25*			

Table 10: Wet weather median concentrations at PWQMN stations

Station ID	Station Location	N	Cl (mg/l)	Total Ammonia as NH3 (mg/l)	Nitrate (mg/l)	Phosphate (mg/L)	TP (mg/L)	TSS (mg/l)	Cu (mg/l)	Fe (mg/l)	Zn (mg/l)
9000100402	Redhill Creek, Albion Falls	3	258	0.030	1.67	0.101	0.118	3.6	0.0026	0.084	0.107
9000100502	Redhill Creek, Queenston Rd	3	158	0.010	0.40	0.049	0.055	4.4	0.0025	0.123	0.016
9000800502	Spencer Creek, Market St.	3	163	0.010	0.78	0.035	0.044	10.2	0.0010	0.139	0.040
9000800602	Spencer Creek, Hwy 5	3	65	0.030	0.38	0.089	0.140	4.8	0.0010	0.206	0.012
9000800702	Spencer Creek, Safari Rd.	3	80	0.070	0.20	0.013	0.036	6.1	0.0003	0.242	0.024
Objectives/Guidelines		*PWQO*					*0.030*		*0.0050*	*0.300*	*0.020*
		CWQG	*120*	*>0.28 variable*	*3.00*			*25*			

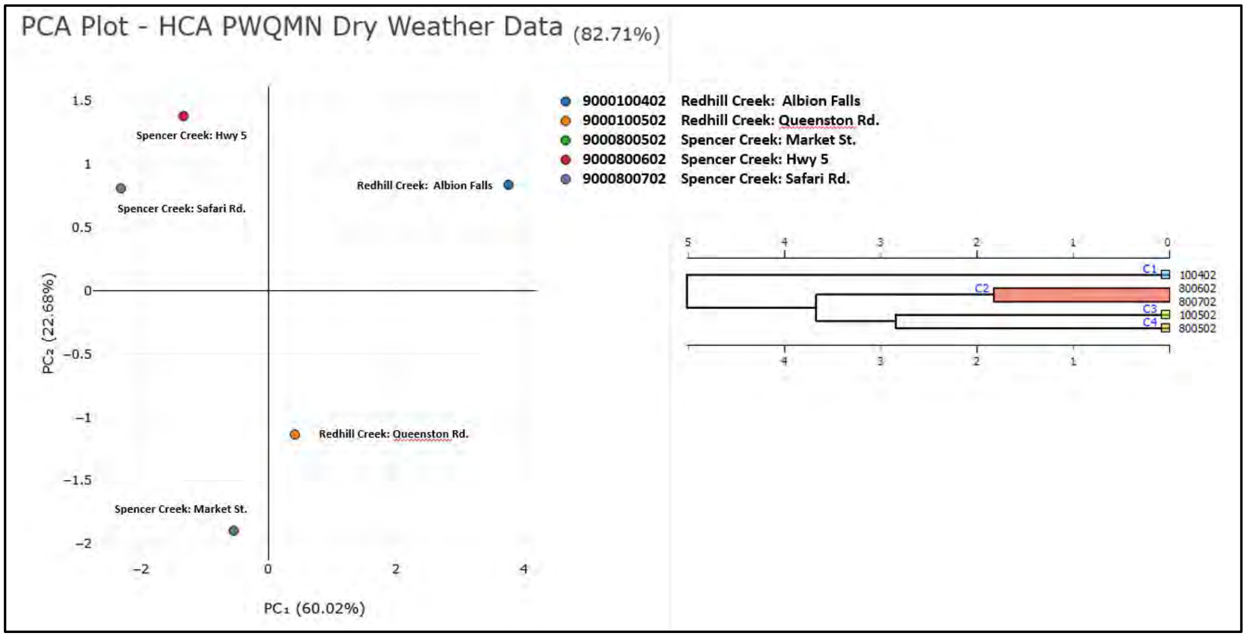

Figure 37: PWQMN PCA Bi-plot Scores (PC_1 vs. PC_2) and Heirarchical Clustering Dendrogram (Top 4 clusters, Euclidean Distance, Ward's linkage) for Dry Weather

was the most significant influence separating the Spencer Creek locations, while chloride, TP, phosphate, and zinc were the primary factors separating the Red Hill Creek Albion Falls location.

The relative lack of clustering yielded by the PWQMN data is not surprising given the wide geographic separation of the sampling locations and the considerable variation in land use. The upstream Spencer Creek location has only about 3% urban land use, increasing to about 9% at the downstream location, whereas the Red Hill Creek locations are both greater than 60%.

6.2 PWQO Univariate Analysis

PWQMN data were predominantly right-skewed and hence non-normally distributed. The limited PWQMN wet weather sampling effort means that the dry weather-wet weather comparison is not as robust as for the SWQP and HCA Cootes tributary results so median wet weather results should be considered illustrative only (Table 10, Figures 38 and 39).

Although there was considerable variation in dry weather results across the six PWQO monitoring locations, chloride, TP, and zinc were the only parameters that exceeded PWQOs or CWQGs. These have been examined more closely and summarized below.

6.2.1 Chloride,

Dry weather median chloride concentrations ranged from approximately 60 mg l^{-1} at the rural upstream Spencer Creek locations (<6% urban land use) to more than 300 mg l^{-1} at the highly urban Red Hill Creek locations (>60% urban land use). The non-parametric ANOVA (Kruskal Wallis) identified that the median chloride concentration at the Red Hill Creek Albion Falls location was significantly ($p<0.05$) greater than the three Spencer Creek locations. Wet weather concentrations were lower than dry weather at both Red Hill Creek locations. This dilution effect was also observed at Red Hill Creek locations in the SWQP results and is consistent with the effect of elevated groundwater concentrations on baseflow in highly urbanized locations (Figure 38). This effect was not apparent at the less urbanized Spencer Creek and Grindstone Creek locations.

6.2.2 Total phosphorus (TP)

Median dry weather TP concentrations ranged from 0.025 mg l^{-1} at the furthest upstream Spencer Creek location to 0.086 mg l^{-1} at the Red Hill Creek Albion Falls location. Phosphate showed the same geographical pattern with a minimum concentration of 0.011 mg l^{-1} and a maximum of 0.056 mg l^{-1} (Table 9, Figure 39). The non-parametric ANOVA showed dry weather concentrations at the Red Hill Creek Albion Falls to be significantly greater ($p<0.05$) than two of the Spencer Creek locations. Total phosphorus and phosphate concentrations increased during wet weather at all locations which reflects the typical effect of runoff in both urban and agricultural settings.

6.2.3 Zinc

The lowest median zinc concentration was 0.005 mg l^{-1} at the Grindstone Creek location and highest was 0.130 mg l^{-1} at the Red Hill Creek Albion Falls location (Figure 38). The non-parametric ANOVAS showed the Red Hill Creek dry weather concentrations to be significantly greater ($p<0.05$) than all three Spencer Creek locations as well as the Grindstone Creek location. Zinc concentrations appeared to decrease during wet weather at the Red Hill Creek locations, most notably at the upstream Albion Falls location. This wet weather dilution effect was similar to that seen for chloride which suggests a dry weather baseflow contribution associated with groundwater.

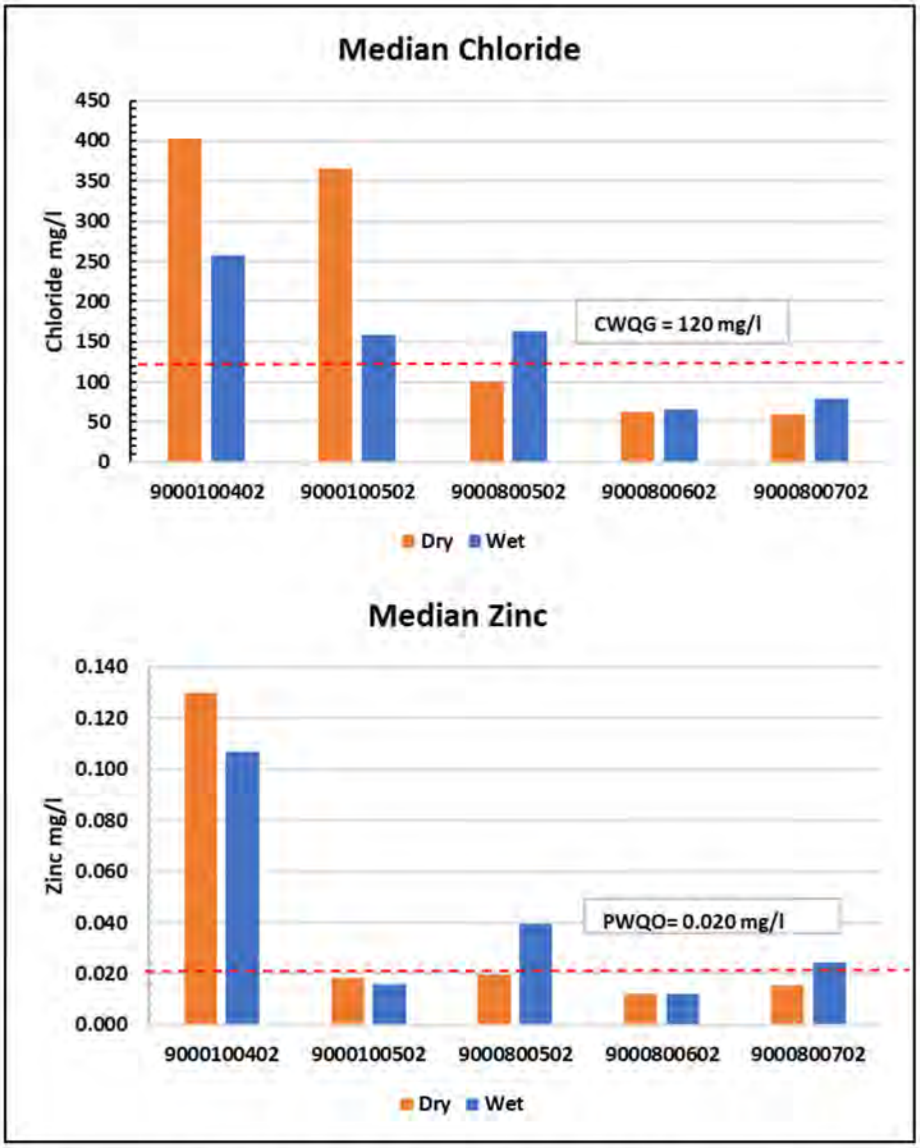

Figure 38: PWQMN Dry and Wet Weather Median chloride and zinc concentrations

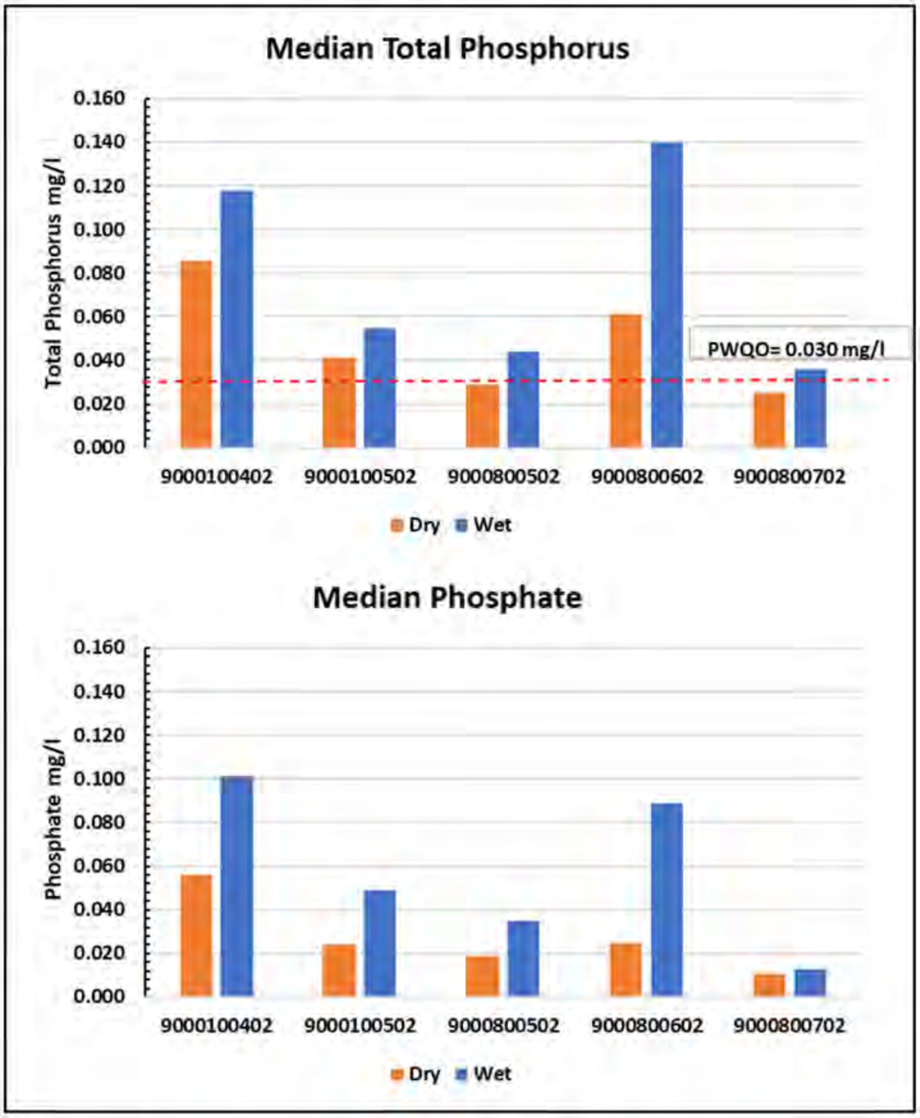

Figure 39: PWQMN Dry and Wet Weather Median total phosphorus and phosphate concentrations

6.3 PWQMN Summary

The PWQMN Program is a long-term, water quality monitoring program designed to monitor ambient (baseline) stream water chemistry generally eight times per year during the ice-free season at over 400 monitoring stations across Ontario[9]. Some monitoring stations have close to 40 years of data which can demonstrate long term trends in water chemistry as well as correlations between land-use activities and water chemistry. In this case for example, the Red Hill Creek Albion Falls location was first sampled in 1979, while the other four current locations were first sampled in 2002. Although this program was not designed to isolate “hotspots”, results are consistent with other sampling programs insofar as they show a distinct difference between the heavily urbanized Red Hill Creek locations and the more rural Spencer Creek and Grindstone Creek locations.

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[9] *https://files.ontario.ca/moe_mapping/downloads/metadata/opendata/Provincial_Water_Quality_Monitoring_Network%20_(PWQMN)_metadata_EN.pdf*

7. MONITORING PROGRAM COMPARISON

7.1 Comparison of SWQP, HCA and PWQMN Monitoring

Comparison of City of Hamilton SWQP, HCA Cootes Tributary (HCA), and HCA PWQMN (PWQMN) monitoring locations (Figure 40) shows that there is relatively little overlap at a local scale. Only three of the 37 sampling locations are within 200 m of each other. In Red Hill Creek, the SWQP Station UO SW1 and PWQMN Albion Falls Station are about 190 m apart. In Chedoke Creek, the SWQP Station CC SW2 and HCA Station CP-11 are approximately 100 m from each other, and SWQP Station CC SW5 and HCA Station CC-3 are within 20 m of each other.

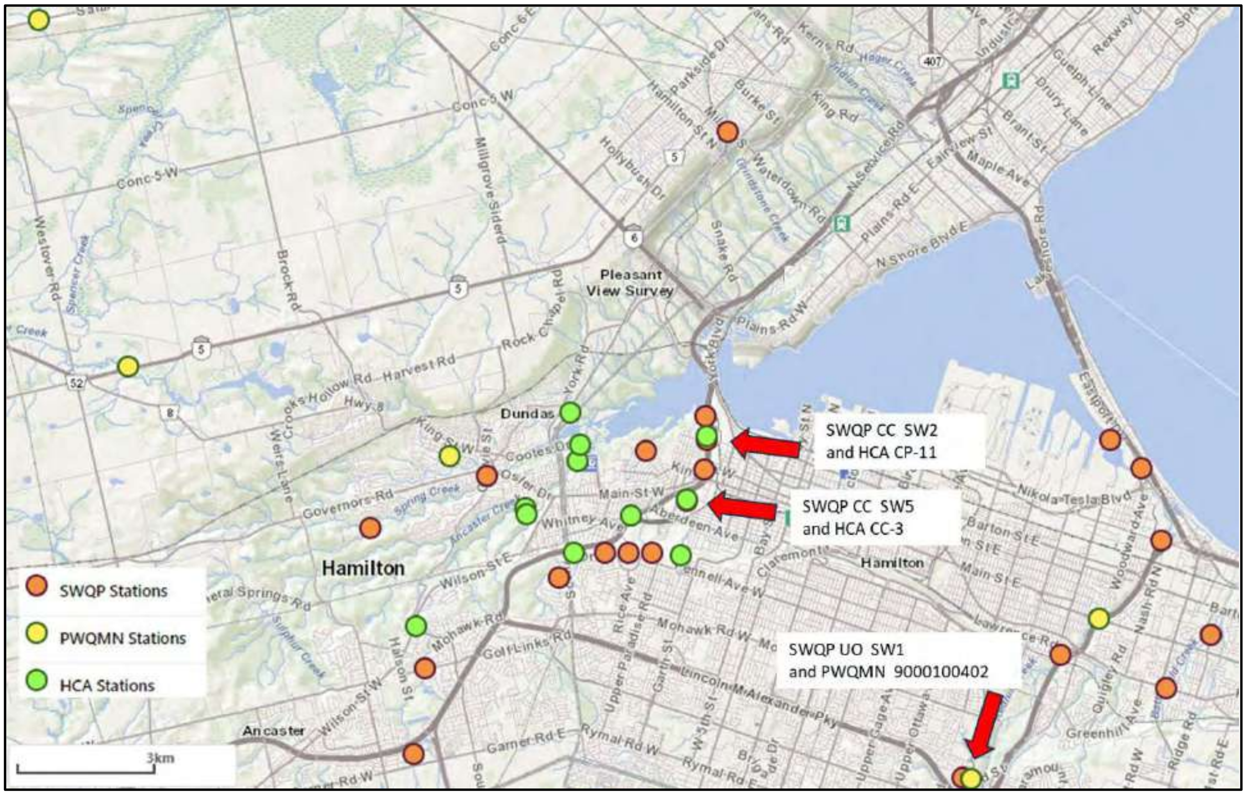

Figure 40: City of Hamilton SWQP, HCA Cootes Tributary, and HCA PWQMN sampling locations

These overlapping sampling locations provide an opportunity to compare estimates of dry and wet weather medians for the common parameters TP, Nitrate, TSS and *E. coli* (Table 11; Figures 41 to 44). The graphical comparisons show similar median concentrations and a statistical comparison using the non-parametric Mann Whitney U test (Wilcoxon rank-sum) showed no significant ($p<0.05$) differences among paired locations for both dry and wet weather. Wet weather PWQMN results were not included given the insufficient sampling frequency.

Table 11: Comparison of SWQP, HCA and PWQMN results at overlapping stations (medians, results of Mann Whitney U test)

	DRY				WET			
Station	**TP (mg/l)**	**Nitrate (mg/l)**	**TSS (mg/l)**	***log E. coli* (mpn/100ml)**	**TP (mg/l)**	**Nitrate (mg/l)**	**TSS (mg/l)**	***log E. coli* (mpn/100ml)**
CC SW2	0.298	2.44	10.5	2.49	0.318	1.60	18.2	3.02
CP-11	0.314	1.98	12.1	2.79	0.254	1.64	20.9	3.15
Sig. diff.	*No*	*No*	*No*	*No*	*No*	*No*	*No*	*No*
CC SW5	0.248	2.74	3.0	2.84	0.320	2.77	10.7	3.04
CC-3	0.268	2.83	7.3	2.92	0.243	2.59	12.5	2.85
Sig. diff.	*No*	*No*	*No*	*No*	*No*	*No*	*No*	*No*
S9000100402	0.086	1.17	5.6					
UO SW1	0.078	1.50	4.4					
Sig. diff.	*No*	*No*	*No*					

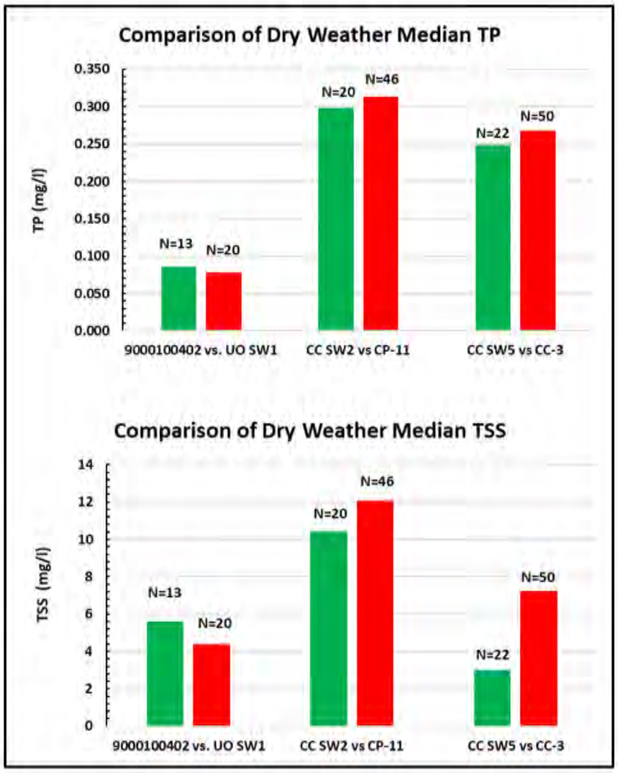

Figure 41: Comparison of dry weather TP and TSS results at similar SWQP, HCA Cootes Tributary, PWQMN locations

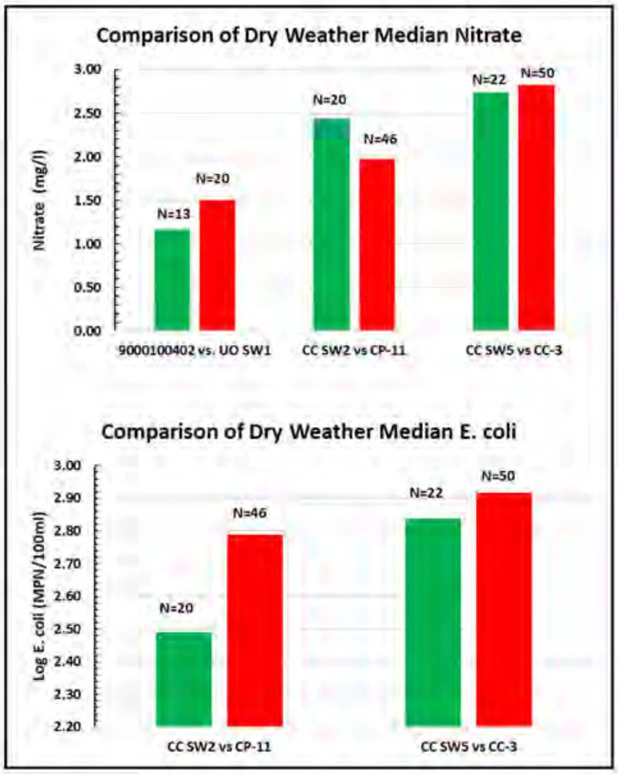

Figure 42: Comparison of dry weather nitrate and E. coli *results at similar SWQP, HCA Cootes Tributary, PWQMN locations*

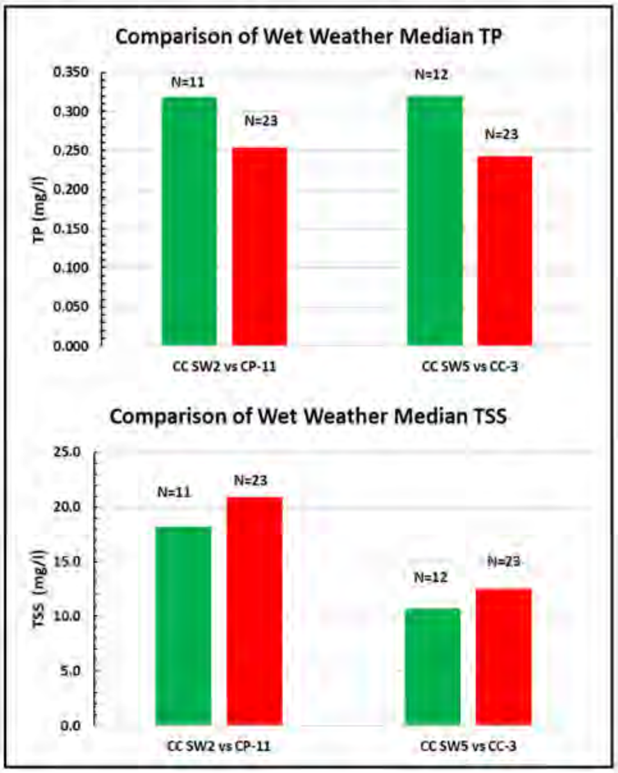

Figure 43: Comparison of wet weather TP and TSS results at similar SWQP, HCA Cootes Tributary, PWQMN locations

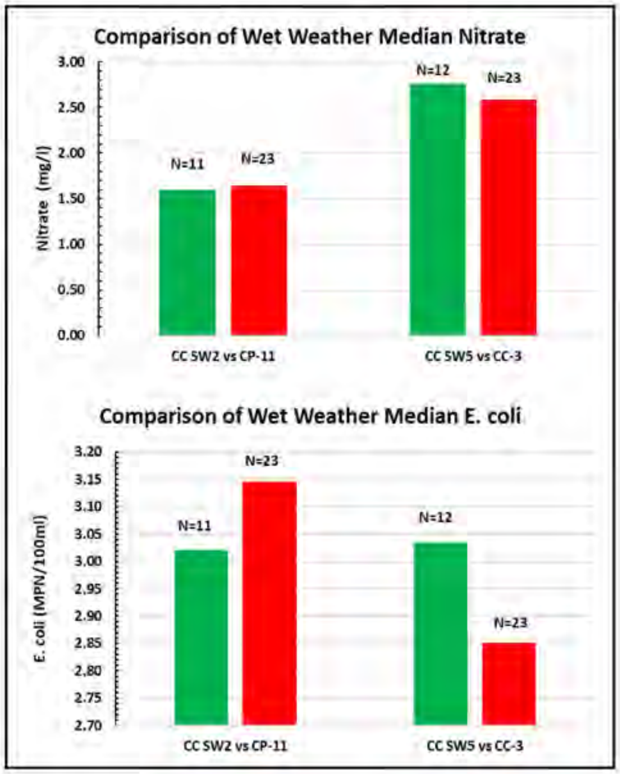

Figure 44:** **Comparison of dry weather nitrate and **E. coli** ***results at similar SWQP, HCA Cootes Tributary, PWQMN locations***

Although it did not include metals analysis, the HCA Cootes Tributary monitoring program had the highest sampling frequency for nutrients, *E. coli* and conventional parameters with more than twice as many dry weather samples as SWQP sampling over the 2021 through 2023 period. This higher sampling frequency means that HCA results represent the most robust estimates of dry weather central tendency for these parameters. However, the statistically significant agreement between HCA and SWQP results indicate that SWQP sampling at Chedoke Creek locations also provided a good indication of dry and wet weather median concentrations despite the less intensive sampling frequency. The agreement between results from different monitoring programs at similar locations is encouraging given the difference in sampling frequencies and sampling dates. It suggests that the underlying spatial patterns revealed by SWQP and HCA monitoring described in preceding sections can be used with confidence.

There was also general agreement between these programs regarding the situation in Chedoke Creek watershed where both SWQP and HCA sampling identified dry weather WQ anomalies in the vicinity of the escarpment. Extreme *E. coli* counts at one of these locations (CC SW 9: Chedoke Creek Mountview Falls at Railtrail Bridge) suggests a possible cross connected sanitary sewer, whereas other anomalies are less extreme and appear to be the result of nutrient and metal enriched ground water contributions to base flow. Groundwater tributary inputs below the escarpment are not surprising given the associated steep hydraulic gradient.

Urban pollution of groundwater is a common global occurrence (Roy and Bickerton 2012) and reflects historical and ongoing accumulations of urban contaminants from inputs. Groundwater contaminants can be considered pseudopersistent in the sense that they result from a combination of long-lived sources and slow transport (Roy and Bickerton 2012). Although this makes direct mitigation challenging, ongoing management of current sources as the result of wet weather flow management will contribute to long term improvement.

7.2 Comparison with 2021 Conservation Halton Monitoring

Conservation Halton (CH) tributary monitoring in Grindstone Creek and Indian Creek was undertaken in 2021 with samples also being analyzed at the City of Hamilton laboratory. A summary of these data was previously undertaken (Boyd and Funk 2022) and although the difference in sampling period and frequency precludes a quantitative assessment, it is possible to qualitatively compare CH 2021 median results for dry and wet weather TP and Chloride with SWQP results (Table 12).

Table 12: Comparison of Conservation Halton and SWQP median concentrations by watershed

Dry Weather					
	Indian Creek	**Grindstone Creek**	**Red Hill Creek**	**Chedoke Creek**	**Spencer Creek***
Total Phosphorus min. (mg/l)	0.038	0.034	0.040	0.041	0.028
Total Phosphorus max. (mg/l)	0.099	0.320	0.303	0.479	0.072
Chloride min. (mg/l)	359	52	208	132	59
Chloride max. (mg/l)	638	431	313	421	190

Wet Weather					
	Indian Creek	**Grindstone Creek**	**Red Hill Creek**	**Chedoke Creek**	**Spencer Creek***
Total Phosphorus min. (mg/l)	0.087	0.042	0.078	0.090	0.028
Total Phosphorus max. (mg/l)	0.115	0.423	0.403	0.524	0.111
Chloride min. (mg/l)	221	52	182	43	71
Chloride max. (mg/l)	356	193	226	285	186

****includes samples from Ancaster Creek and Spring Creek***

For TP this shows that the Grindstone Creek dry weather “hotspot” (at Millgrove) had a relatively similar concentration to the Red Hill Creek maximum (downstream of the Woodward Ave. WWTP) but was substantially lower than the Chedoke Creek maximum (at CC SW9). Neither Spencer Creek nor Indian Creek exhibited a dry weather TP anomaly. Wet weather TP median results show a wider range of minimum median concentrations with Spencer Creek remaining below the PWQO of 0.030 mg l^{-1} (in Spring Creek). Maxum median TP concentrations during wet weather were relatively similar at the Grindstone Creek and Red Hill Creek “hotspot” locations but, as during dry weather, the maximum concentration occurred at the Chedoke Creek “hotspot”. Neither Spencer Creek nor Indian Creek exhibited a wet weather TP anomaly.

Median dry weather chloride results showed the Indian Creek “hotspot” to exceed the other elevated urban concentrations observed in Grindstone Creek, Red Hill Creek and Chedoke Creek. Wet weather median chloride concentrations showed a similar dilution effect in Indian Creek and Grindstone Creek to that observed in Red Hill Creek and Chedoke Creek.

This qualitative comparison reflects a similar pattern of association between urbanized landscapes and impaired water quality across the entire Hamilton Harbour watershed although it suggests that there are no TP anomalies to be investigated in the Indian Creek watershed.

8. SUMMARY AND RECOMMENDATIONS

8.1 Summary of Findings

City of Hamilton SWQP and HCA Cootes Tributary Monitoring data were predominantly non-normally distributed (typically right skewed) but statistically significant dry and wet weather anomalies for nutrients and *E. coli* in the Chedoke Creek and Red Hill Creek watersheds were identified using a non-parametric (rank-based) ANOVA (Kruskal Wallis) with post-hoc Dunn's test.

Mapping near-minimum (25th percentile) concentrations showed good congruence with the statistical findings and provided a simple way of geographically flagging locations potentially worthy of subsequent investigation.

SWQP and HCA water quality results were clearly associated with upstream land use; urbanized locations typically exhibited significantly more degraded water quality than more rural and agricultural locations.

Water quality guidelines and standards for nitrate, unionized ammonia, copper, and lead were met in more than 50% of samples at most locations.

Analysis of SWQP dry weather data for nutrients and other contaminants of concern flagged TP and *E. coli* anomalies at Chedoke Creek location CC SW9 suggestive of a sewage-related source as well as Chedoke Creek and Red Hill Creek locations where the influence of chloride, nutrient and metal-enriched groundwater is having a strong influence on dry weather baseflow concentrations.

HCA dry weather sampling showed anomalies within the Chedoke watershed for both *E. coli* and TP with TP concentrations predominantly in the form of soluble P suggesting that elevated dry weather concentrations were associated with phosphate enriched groundwater. The greatest TP anomaly in HCA results was at Station CC-9 (Chedoke Creek downstream of Middle Chedoke Falls) with the greatest *E. coli* outlier occurring at CC-7 (Chedoke Creek upstream of Upper Princess Falls).

HCA dry and wet weather concentrations of total ammonia, nitrate, and TSS were generally below CWQG values, however total ammonia and nitrate concentrations were markedly higher at Chedoke Creek locations than Ancaster Creek and Borer’s Creek locations.

HCA wet weather data showed a dilution effect for total ammonia at Chedoke Creek Station CP-11 (Chedoke Creek downstream of Kay Drage Park Bridge) and for nitrate at all Chedoke Creek locations.

SWQP showed similar wet weather dilution effects for chloride, nitrate, ammonia, and zinc at several stations indicating that there are watershed locations where the dry weather influence of degraded groundwater exceeds the influence of storm water runoff during wet weather events.

Three SWQP locations had persistent and elevated zinc concentrations; two of these were also associated with anomalous E. coli results (Stations CC SW9 and UO SW1) while the third (Station CC SW10: Chedoke Creek at Outfall near 130 Daffodil Crescent) was not associated with any other contaminant issues. SWQP Dry weather anomalies are suggestive of a groundwater influence on baseflow zinc concentrations driven by the dissolved form which is of greatest toxicological concern.

Zinc concentrations at two SWQP locations (CC SW9 and UO SW1) persistently exceeded the CWQG acute exposure threshold of 0.037 mg l^{-1} for dissolved zinc which suggests it may be exerting toxic effects on aquatic life in some regions of the heavily urbanized watersheds.

Collectively, monitoring results suggests that initial follow up efforts associated with identifying and managing anomalous sources of *E. coli* and TP can be concentrated at a small subset of program monitoring locations. More specifically, comparison of SWQP results with water quality guidelines, standards and locally derived benchmarks flagged Station CC SW9 (Chedoke Creek Mountview Falls at Railtrail Bridge) and Station UO SW1 (Red Hill Creek at Albion Falls) and BatC SW1 (Battlefield Creek at Lake Ave, Park) as high priority locations for investigation of *E. coli* sources as well as CC SW9 and CC SW3 (Chedoke Creek at Glen Rd. Outfall) as high priority locations for management of TP.

Four SWQP locations and four HCA Cootes Tributary Monitoring locations had consistently good water quality results and frequently met water quality standards and guidelines due to the predominance of upstream agricultural or natural land uses. These were: Ancaster Creek near Maple Lane Park (AC SW4); Grindstone Creek at Mill Street South (GC222 SW1); Spring Creek West of Ogilvie Street (SprC SW1); Spring Creek at John White Trail Bridge (SprC SW2); Lower Ancaster Creek Stations AC-1, AC-2 and AC-3, and the Borer’s Creek station CP-18.

Comparison of results from the three locations where SWQP, HCA and PWQMN monitoring locations overlapped showed similar dry and wet weather medians for TP, nitrate, TSS and *E. coli* and a statistical comparison confirmed that SWQP results were comparable to higher frequency HCA results.

Although PWQMN data were generally consistent with SWQP results at the Red Hill Creek Albion Falls location, the program is poorly suited for identifying potential hot spots given the low frequency of sample collection and the emphasis on rural and agricultural watersheds.

A qualitative comparison of SWQP and 2021 Conservation Halton tributary monitoring in the Indian Creek and Grindstone Creek watersheds indicated a generally similar pattern of impaired water quality associated with urbanized landscapes although no TP anomalies were observed in Indian Creek.

8.2 Recommendations

8.2.1 Water Quality Criteria and Metrics for Tracking Improvements

Although multivariate analysis successfully flagged sampling locations with poor water quality, the separation was driven by different contaminants at different locations and consequently identification of univariate outliers for contaminants of primary concern (e.g. *E. coli*, TP) provides a straightforward, practical approach to identifying potential hot spots.

The ubiquitous presence of elevated chloride, *E. coli*, TP and zinc levels in urbanized watersheds renders provincial and federal water quality guidelines and standards impractical for evaluating abnormally degraded water quality. However, thresholds derived from the upper quartile of selected SWQP data provide an objective basis for flagging locations potentially meriting additional assessment.

One key finding to emerge from the watershed reconnaissance monitoring effort, is the presence of elevated zinc concentrations, particularly during dry weather presumably due to the presence of soluble zinc in groundwater. For this reason, it may be appropriate to further investigate sources of zinc and the potential toxic effects of chronic zinc exposure on aquatic organisms.

8.2.2 Optimized and Coordinated Monitoring

Only three of the 37 SWQP, HCA Cootes Tributary, and PWQMN sampling locations were situated close to each other so these programs do not warrant a location review as the result of redundant sampling effort.

PWQMN monitoring should be maintained with the awareness that it is designed to assess long-term trends in baseflow water quality and is not compatible with SWQP and other HCA monitoring objectives.

Lower frequency SWQP sampling yielded similar results to HCA Cootes Tributary monitoring at two similar sampling locations suggesting that it may be possible to redeploy some of the HCA sampling effort if it becomes desirable to increase spatial coverage in Cootes watersheds.

Both SWQP and HCA Cootes Tributary monitoring provide good spatial coverage of the Chedoke Creek watershed so HCA program managers may wish to review and compare program objectives and design with SWQP managers at the City of Hamilton potentially leading to shared data access. There may be opportunities to expand the HCA HHRAP sampling program, to include additional parameter analysis (such as metals and chloride), to be consistent with the City SWQP and to expand the spatial coverage for parameters of concern.

HCA and SWQP sampling results showed consistently good water quality during dry and wet weather at sampling locations in lower Ancaster Creek, Spring Creek, Grindstone Creek, and Borer’s Creek so if additional resources are required to investigate anomalies, it may be possible to reduce the sampling effort at these locations.

8.2.3 Nutrient Management Plan Development: Source Identification and Remedial Actions

SWQP and HCA Cootes Tributary monitoring demonstrated the expected finding that locations with more highly urbanized upstream land uses exhibited more degraded water quality. As previously noted, the effects of urban environments on water quality are well documented with nutrient sources including chemical lawn fertilizer, soil, leaf litter, pet waste, construction activities, and leaking or cross connected sanitary sewers. Sources of metals include domestic and industrial sewage, combustion of solid wastes and fossil fuels, road surface runoff, corrosion of metal surfaces, tire debris and motor oil and grease. Additionally, winter road deicing programs contribute to elevated chloride concentrations in winter runoff and year-round ground water.

The significant reduction in lead concentrations following it phasing out as a fuel additive illustrates the potential for regulatory action to yield water quality improvements, but there are limited options for additional actions of this scope. Eliminating or restricting phosphate in household lawn fertilizers has been successfully implemented in several U.S. states [10] however numerous phosphorus free options are already available in Ontario so consumer information campaigns may be able to achieve desirable results.

The water quality sampling undertaken by the City of Hamilton (SWQP) and HCA (Cootes Tributary monitoring) has identified one location that strongly indicates a cross connection due to extremely high dry weather E. coli counts and P concentrations (CC SW9) as well as several others where elevated dry

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[10] *https://www.cga.ct.gov/2012/rpt/2012-R-0076.htm*

weather concentration may merit a closer look. Additional localized monitoring near potential hotspots and assessment of historical land uses should be pursued, potentially through reallocation of resources from current monitoring locations that consistently exhibit good water quality. In many cases, however, current data suggest that these dry weather anomalies result from the pseudopersistent effect of degraded ground water quality linked to historical, long-term accumulations in urban environments as the result of sources listed above.

Since these historical inputs will frequently have resulted from urban runoff during wet weather, the best course of action will be to implement an adaptive management approach to improving the health and function of Hamilton Harbour tributaries and the harbour (Metro Vancouver 2014). This approach will seek to apply monitoring results so as to achieve the most cost effective and measurable improvements. For example, it may be worthwhile to consider incorporation of Stormwater Management Facilities (SWMFs) as part of relevant ongoing wet weather flow management programs such as the City of Hamilton Real-Time Control project [11]. In addition to improving water quality through the reduction of nutrients, heavy metals, and pathogens, urban stormwater management will yield a range of additional co-benefits such as reduced basement flooding in areas serviced by combined systems, protection of stormwater conveyance infrastructure, and erosion and flood control.

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[11] *https://www.hamilton.ca/home-neighbourhood/environmental-stewardship/our-harbour/current-clean-harbour-projects#real-time-control*

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APPENDIX A: WATER QUALITY ANALYSIS

Hamilton SWQP analysis:

Carbonaceous Biochemical Oxygen Demand (cBOD)
Conductivity
Dissolved Oxygen (DO)
pH
Temperature
Ammonia as N
Un-ionized Ammonia
Chloride (Cl)
Escherichia coli (E. coli) *bacteria*
Hardness
Nitrate (NO3)
Nitrite (NO2)
O-Phosphate (PO4)
Total Kjeldahl Nitrogen (TKN)
Total Phosphorus (TP)
Total Suspended Solids (TSS)
Aluminum (Al)
Antimony (Sb)
Arsenic (As)
Barium (Ba)
Beryllium (Be)
Bismuth (Bi)
Boron (Bo)
Cadmium (Cd)
Calcium (Ca)
Chromium (Cr)
Cobalt (Co)
Copper (Cu)
Iron (Fe)
Lead (Pb)
Lithium (Li)
Magnesium (Mg)
Manganese (Mn)
Molybdenum (Mo)
Nickel (Ni)
Potassium (K)
Selenium (Se)
Silicon (Si)
Silver (Ag)
Sodium (Na)
Strontium (Sr)
Thallium (Tl)
Tin (Sn)
Titanium (Ti)
Tungsten (W)
Uranium (U)
Vanadium (V)
Zinc (Zn)

Hamilton Conservation Authority - Cootes Tributary Monitoring:

Total Suspended Solids
Nitrite as N
Nitrate as N
Volatile Suspended Solids
Phosphorus Total
Ammonia + Ammonium as N
o-Phosphate as P
Escherichia coli

Hamilton Conservation Authority - PWQMN Monitoring:

Hardness
Phosphorus; total
Nitrogen; total
Conductivity
pH
Alkalinity
Solids; suspended
Carbon; dissolved organic
Silicon; reactive silicate
Carbon; dissolved inorganic
Chloride
Nitrogen; nitrate+nitrite
Nitrate
Phosphorus; phosphate
Nitrogen; nitrite
Nitrogen; ammonia+ammonium
Solids; dissolved
Solids; total
Oxygen demand; biochemical
Chlorophyll A
Chlorophyll B
Total Chlorophyll A
E. coli *count per 100 mL*
Calcium
Aluminum
Arsenic
Antimony
Barium
Beryllium
Bismuth
Boron
Cadmium
Cobalt
Copper
Chromium
Iron
Lead
Lithium
Magnesium
Manganese
Molybdenum
Nickel
Potassium
Selenium
Silver
Sodium
Strontium
Thallium
Tin
Titanium
Uranium
Vanadium
Zinc

APPENDIX B: SWQP DATA SUMMARY AND ANALYSIS

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APPENDIX C: HCA COOTES TRIBUTARY DATA SUMMARY AND ANALYSIS

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APPENDIX D: PWQMN DATA SUMMARY AND ANALYSIS

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