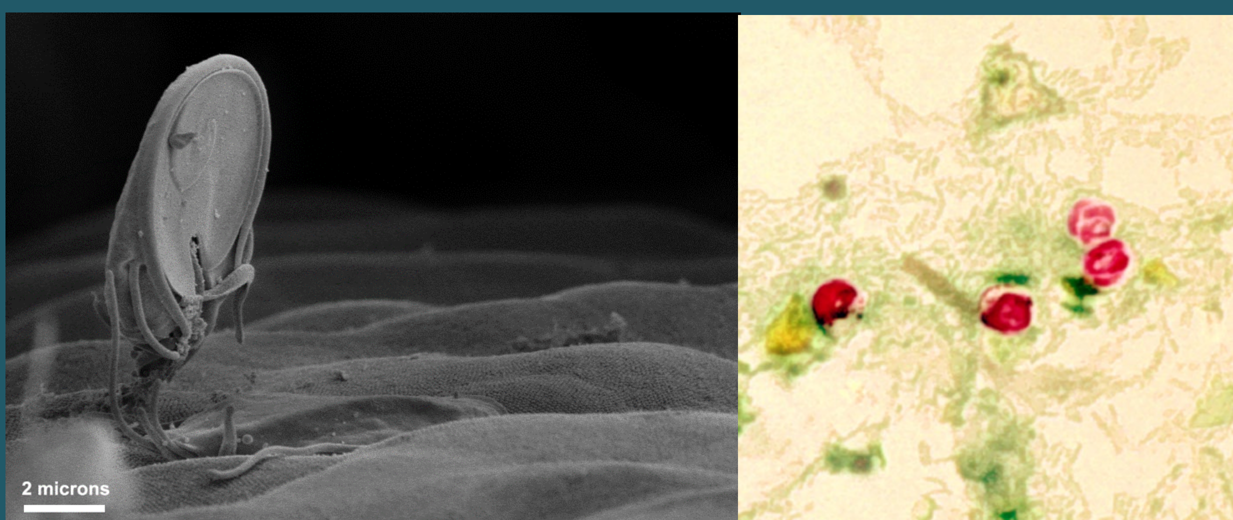
A Proof-of-Concept Pilot Study Transboundary Monitoring of Environmental Factors and their Influence on Waterborne Protozoan Acute Gastrointestinal Illnesses in Cities that Source Water from the Great Lakes

Phase 2: Analysis



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Front cover photos:

Black and white photo on the left: This scanning electron microscopic (SEM) image depicted a *Giardia* sp. intestinal protozoan situated in an upright position on the mucosal surface of the intestine. The ventral adhesive disk, which facilitates adherence to the intestinal surface, can be seen on the underside of the organism. Image credit: US Centers for Disease Control and Prevention/Dr. Stan Erlandsen. PHIL: ID# 11645. (1999). Public domain.

Color photo on the right: This photomicrograph revealed the morphologic details of *Cryptosporidium parvum* oocysts, which had been stained using the modified acid-fast method. These oocysts exhibit a bright red coloration when using this staining technique, and in this case, you'll note the sporozoites that were made visible inside the two oocysts on the right. Sporozoites are the nucleated, motile stage of development through which many protozoans pass such as *C. parvum*, on their way to becoming adults, and represent a very infectious form of these organisms. When mature, the sporozoites will be liberated from the oocysts. Image credit: US Centers for Disease Control and Prevention/DPDx. PHIL: ID# 7879. Public domain.

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List of Acronyms

AGI	acute gastrointestinal illness
DWTP	drinking water treatment plant
FSA	Forward Sortation Area
GIS	geographical information system
HPAB	Health Professionals Advisory Board
IJC	International Joint Commission
qAIC	quasi-Akaike's information criterion

Executive Summary

The International Joint Commission's (IJC) Health Professionals Advisory Board (HPAB) identified the growing need to integrate transboundary environmental and human health data to enable more informed protection and restoration decisions related to ecosystems and public health and, ultimately, to reduce the environmental burden of disease (Bassil et al. 2015). The HPAB initiated a pilot study with the goal of enabling more effective use of existing health and environmental data to monitor human health of the Great Lakes and to further our understanding of associations between environmental factors and human health outcomes in the Great Lakes region (International Joint Health Professionals Advisory Board 2014). This pilot study assessed the feasibility of binational (Canada and United States) surveillance of sporadic protozoan waterborne acute gastrointestinal illness (AGI) and environmental risk factors by exploring these relationships in two US and two Canadian cities using Great Lakes as a drinking water source: Hamilton and Toronto, Ontario (Lake Ontario) and Green Bay and Milwaukee, Wisconsin (Lake Michigan). Climate change is expected to impact several factors linked to gastrointestinal illness giving some urgency to assessing our capacity to detect and monitor this relationship.

During Phase 1 of this effort, data were sought for cases of selected gastrointestinal illnesses (cryptosporidiosis and giardiasis), meteorological conditions and drinking source water quality indicators for drinking water intakes for four cities within the Great Lakes region of Canada and the United States from 2003 to 2016 (**Appendix 6.1**). The quality, quantity and comparability of available data collected allowed the examination of the relationship between risk of AGI, extreme precipitation events and drinking water sources in the four cities (International Joint Commission Health Professionals Advisory Board 2017a). The study presented here describes Phase 2 and examines whether the data collected enable observational epidemiologic studies using weather, water quality and disease outcomes. Interpretation and visualization of the effects of weather and other risk factors on the incidence of AGI was facilitated by using geographical information systems (GIS).

Phase 2 used data collected as part of Phase 1 for all four cities from January 1, 2009 through August 31, 2014 (dates for which consistent data were available at all locations) to examine the relationship between onset of illness, meteorological conditions including extreme precipitation (rain and snow) events, and indicators of water quality from drinking water treatment plant intakes. Geospatial analysis, time-series analysis and a series of distributed lag nonlinear regression models were used to:

1. Compare trends,
2. Estimate statistical associations between the various sets of environmental, human health and spatial data, and
3. Examine potential risk for AGI for each city.

Model results indicated that the risk of AGI was increased following an abrupt precipitation spike (e.g., 90th percentile precipitation event preceded by a dry period) in Hamilton (one-week lag) and Toronto (four-week lag). Milwaukee showed similar increase in relative risk of AGI following the abrupt precipitation spike (four-week lag), but the increase was not statistically significant. For Green Bay, no relationship was detected.

This study's two phases aimed to use monitoring and surveillance information from these four municipalities to illustrate how comparable binational health and environmental data can be combined and contrasted to develop and test hypotheses about environment-health interactions in the Great Lakes. Understanding interactions of meteorological conditions and drinking source-water quality with AGI incidence can support health protection recommendations that address the integrated ecology, but politically divided geography, of the Great Lakes. Such understanding also lays a foundation for coordinated testing and potential interventions to address vulnerabilities in municipal drinking water systems. With such knowledge, jurisdictions may better plan and manage activities to reduce AGI caused by contaminated drinking water and plan for climate change and the projected increased of extreme weather events, which will increasingly test the vulnerability of our municipal water systems.

This work demonstrates that integrated, comparable, binational environmental and human health data can be obtained and used for research and modeling to inform efforts to protect overall human health in the Great Lakes (International Joint Commission Health Professionals Advisory Board 2017a).

Key findings from this work include:

- The relative risk of sporadic AGI one to four weeks after extreme precipitation (greater than or equal to a 90^{th} percentile precipitation event) preceded by a dry period was significantly greater for Hamilton and Toronto. Milwaukee showed a similar pattern but the elevation in risk was not statistically significant (**Figure i** below).
- In many cases, the addition of turbidity and total coliforms improves the fit of the model to the observed data—based on the quasi-Akaike's information criterion statistic—and that improvement in model fit varied based on which drinking water treatment plant intake data was used. Turbidity had the largest impact on improving the fit, though the inclusion of total coliforms also improved most models.

These case studies in the four cities were done to assess the feasibility of using binational databases for the assessment of AGI risk from drinking water in the Great Lakes. Our work revealed limitations in data access, availability and harmonization as barriers (Bassil et al. 2015) particularly for health data access. Despite long-standing environmental monitoring programs in both countries, much of the environmental data for this study had to be assembled from a combination of national, state or municipal entities. In each country and binationally, to our knowledge, no clearinghouse exists for drinking water source quality data. We did not examine the impact of changes in relative contributions of water utilities with multiple water treatment plants and intakes, like those of Toronto and Milwaukee. Such an analysis could provide additional insights into drivers of increased AGI risk.

The increasing availability of digital data from public health outbreak investigations may allow confounding risk factors to be included in large-scale analyses in the future. Additional data and detail could also help explain the variation in lag time for peak risk for each city. Potential explanatory factors are variation in the time between testing and reporting and perhaps differences in health access and diagnostic delays.

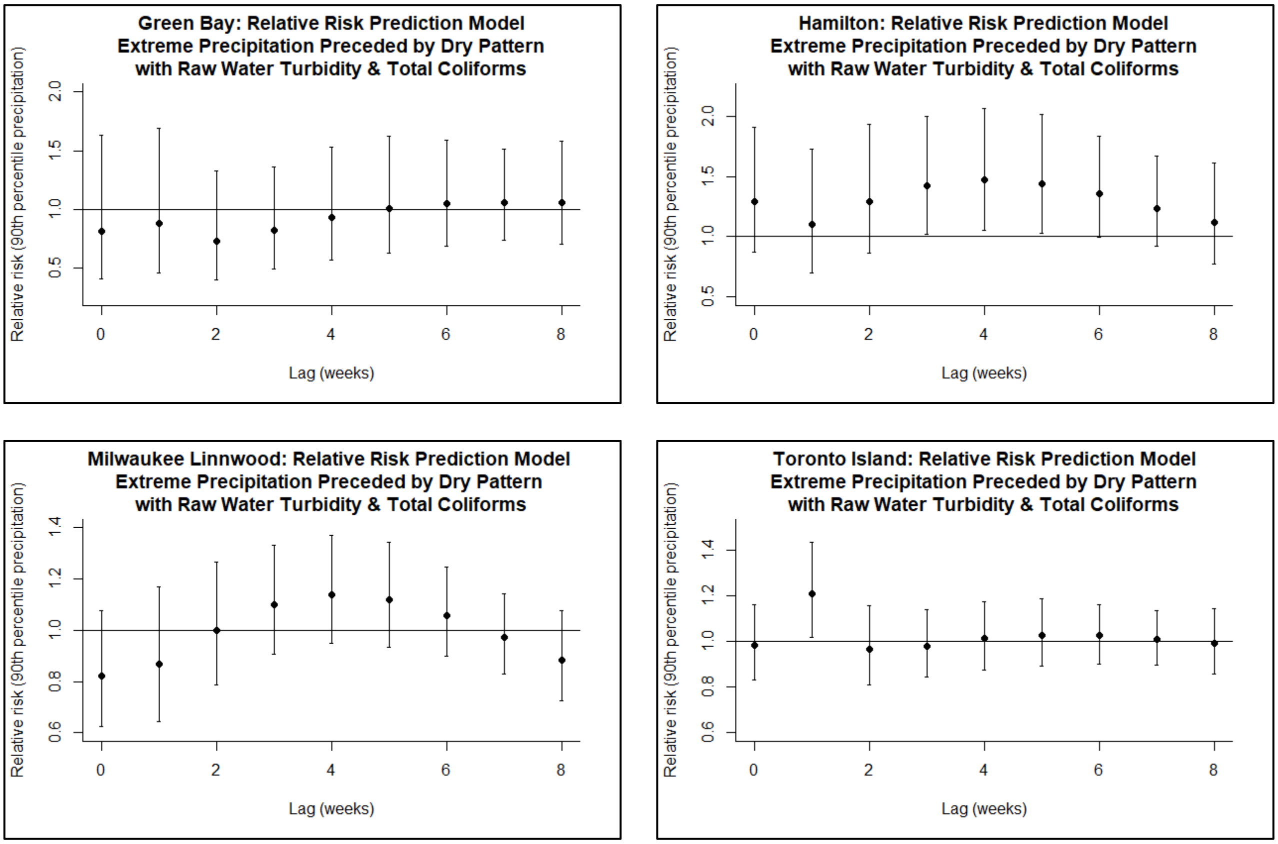

Figure i: Relative risk of AGI (cryptosporidiosis and giardiasis) following extreme precipitation (greater than or equal to a 90th percentile event) preceded by a dry period.

Following review of this work, the HPAB recommends that the governments of Canada and the United States, as Parties to the Great Lakes Water Quality Agreement (hereafter, the Parties):

a. Expand this work to assess acute gastrointestinal illness risks for other Great Lakes and cities that source their drinking water from the Great Lakes and connecting channels, such as Thunder Bay (Lake Superior), Sarnia (Lake Huron), Windsor (Detroit River), London (both Lake Erie and Huron) and Mississauga (Lake Ontario) in Ontario, Canada, and Duluth, Minnesota (Lake Superior), Chicago, Illinois (Lake Michigan), Saginaw, Michigan (Lake Huron), Cleveland, Ohio (Lake Erie) and Niagara Falls, New York (Niagara River) in the United States. Health data were provided through central databases at the state and provincial levels, therefore collaboration with state and provincial governments would be critical to assembling necessary data.
b. Establish a binational drinking water source quality and human health clearinghouse for cities that source water from the Great Lakes. This will require developing partnerships with both municipal water systems, health data providers

and existing organizations, such as the Huron to Erie Drinking Water Monitoring Network.[1]

c. Include indicators of drinking source water quality at drinking water treatment plant intakes as part of their State of the Great Lakes report. Source water monitoring and reporting continues to be of vital importance in understanding the risks faced by those reliant on the Great Lakes for their water supply.

The HPAB notes that continuation of this work should position the IJC as instrumental in harmonizing drinking source water indicators and support real progress on monitoring human health in the Great Lakes.

These results emphasize that source water monitoring and reporting continues to be of vital importance for understanding the risks faced by those reliant on the Great Lakes for their water supply. The governments of Canada and the United States currently only report on finished water quality in the triennial State of the Great Lakes reports as part of their responsibilities under the Great Lakes Water Quality Agreement (Canada and the United States, 2017). The HPAB notes that the IJC could be instrumental in enabling the integration, harmonization and analysis of binational data relevant to source water quality and other environmental (e.g., climate) and human health indicators. In doing so, the IJC would accelerate progress on monitoring, modeling and preventing human health problems across political boundaries in the Great Lakes basin. This knowledge is of increasing importance as public health authorities work to anticipate how changes in future extreme precipitation events will influence protozoan waterborne disease risk.

[1] Network data is available at: waterdatadetroit.azurewebsites.net/About and a report explaining the network program can be downloaded from: semcog.org/desktopmodules/SEMCOG.Publications/GetFile.ashx?filename=HuronToErieRealTimeDrinkingWaterMonitoringAugust2020.pdf.

1.0 Introduction

The residents of the Great Lakes region enjoy widespread ecosystem service from the lakes. An estimated 40 million people on both sides of Canada and the United States' shared border source their drinking water from the Great Lakes. To support continued enjoyment of these vital services, the Great Lakes states and provinces of both countries all adhere to similar, but slightly different, bacterial water quality standards based on estimates that ensure a low risk of illness in humans. In Ontario, Canada, statues that protect source water and drinking water include the Ontario Clean Water Act, 2006 and the Ontario Safe Drinking Water Act, 2002, that together form a regulatory framework for a comprehensive management approach. In the United States, two significant federal statutes contribute to the protection of source water and drinking water, the Clean Water Act of 1972 and the Safe Drinking Water Act of 1974. Keeping source water and drinking water safe for the residents of the Great Lakes basin is one of the most important aspects of the Great Lakes Water Quality Agreement, and the International Joint Commission (IJC) has a responsibility to provide advice to help the federal governments of Canada and the United States (the Parties) to achieve these environmental and human health related goals.

The IJC's Health Professionals Advisory Board (HPAB) previously identified new human health indicators to aid in monitoring the Great Lakes as a safe environment for swimming, fishing and drinking, that the IJC recommended to the governments of Canada and the United States (International Joint Commission Health Professionals Advisory Board 2014). The governments of Canada and the United States currently only report on finished water quality in the triennial State of the Great Lakes reports as part of their responsibilities under the Great Lakes Water Quality Agreement (Canada and the United States, 2017). These recommendations tied the assessment objectives of the Great Lakes Water Quality Agreement to the health of residents and resource users of the Great Lakes basin. These included proposed indicators, measures, rationales and processes for monitoring drinking water source quality by the governments of Canada and the United States. The source water monitoring approach provides a more direct means for the IJC to assess whether the Great Lakes continue to "be a source of safe, high-quality drinking water" (Canada and the United States, 2012), as compared to the finished (e.g., treated) drinking water indicator currently used by the Parties in their State of the Great Lakes reports (Canada and the United States, 2017).

Drinking water quality is managed through the multipronged approach of protecting source water and by engineering systems to treat raw water for distribution to customers for potable uses (e.g., drinking and cooking). Several factors may potentially disrupt existing public health protections including the impacts of combined and sanitary sewer overflows and septic systems (Bower 2005; McLellan et al. 2007);[1] decay of legacy infrastructure (American Society of Civil Engineers 2020; American Water Works Association 2019; Canadian Infrastructure Report Card

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[1] Also note a related study by the Health Professionals Advisory Board report: The Great Lakes water quality centennial study report: A proof-of-concept pilot study of transboundary monitoring of environmental factors and their Influence on waterborne acute gastrointestinal illness (AGI) in cities that source water from the Great Lakes, phase 1: feasibility study; when published the report will be uploaded to ijc.org/en/hpab/library/reports.

2019); changing weather patterns from climate change (Khan et al. 2015); changing shoreline use from agriculture practices, loss of greenspaces and stormwater management (St-Hilaire et al. 2016); changing types and distributions of pollutants (including nutrient pollution); invasive or re-emerging animal and plant species (e.g., quagga mussels and cyanobacteria); and antimicrobial resistance (World Health Organization 2015). Safe drinking water requires a match of source water quality to appropriate water treatment capabilities, and both are undergoing dynamic change.

A source water monitoring approach, and the assessment it supports, requires effort to integrate binational data sets. Many government, academic and research institutions already collect environmental data that may be relevant to understanding exposure-human health associations when appropriately linked with existing health data. A related HPAB investigation into the challenges of merging binational environmental and health databases identified limitations of data access, availability and harmonization as barriers (Bassil et al. 2015). The use of case studies was recommended to further refine and focus binational database integration activities, with the aim of examining any relationships between environmental hazards and human illness across the Great Lakes. This pilot investigation of waterborne acute gastrointestinal illnesses (AGI) is designed to show, in a proof-of-concept fashion, how some of those indicators can be used in this transboundary setting, linking health and environmental data and examining challenges to database merging as identified by Bassil et al. (2015). The HPAB noted that these issues would impact the feasibility and application of its recommended approach for indicator monitoring and the IJC's assessment.

With this work, the HPAB aims to demonstrate that integrated, comparable binational environmental human health data can be obtained and used for monitoring, research and modeling to protect overall human health in the Great Lakes.

With this work, the HPAB aims to demonstrate that integrated, comparable binational environmental and human health data, can be obtained and used for monitoring, research and modeling to protect overall human health in the Great Lakes. Phase 1 assessed the feasibility of collecting environmental and health data in a transboundary setting between Canada and the United States to establish potential associations between variables in these data (International Joint Commission Health Professionals Advisory Board 2017a). Four cities were selected for this study: Hamilton and Toronto, Ontario in Canada, and Milwaukee and Green Bay, Wisconsin in the United States. These four cities own and operate drinking water utilities that draw raw surface water from the Great Lakes for treatment and distribution to their customers. These four cities were chosen because they each have data from well-established public health surveillance programs, are located in only two country subdivisions (Ontario and Wisconsin) that minimized the correspondence and approvals through multiple provincial or state systems and had existing relationships with the HPAB.

The HPAB evaluated these data streams for resolution, quality, time frame and metadata. All four cities provided illness data on sporadic cases of giardiasis and cryptosporidiosis between January 1, 2009 through August 31, 2014 to serve as the dependent variables in the analysis. Of all the reportable infectious diseases in Ontario and Wisconsin, these two illnesses are the most likely to be waterborne and are resistant to common water treatment methods (Canadian Council of Ministers of the Environment 2004).

Sporadic cases of AGI were studied instead of outbreaks because these cases are more frequent (Hunter et al. 2004; Lochlainn et al. 2019) and more likely to be related to weather or climate factors than outbreaks, which are generally linked to specific events (Chhetri et al. 2017; Insulander et al. 2005). Risk factor data collected included measures for water quality from source water intakes using the recommended indicators for biological hazards of source water (International Joint Commission Health Professionals Advisory Board 2014). The independent variables sought for our analysis included measurements at the water utilities' raw water intakes for the HPAB's five recommended indicators of biological hazards of source water: *Escherichia coli*, *Cryptosporidium parvum, Giardia lamblia*, nitrates and turbidity. Additional independent variables included environmental and meteorological data for extreme precipitation events, air temperature, wind speed and direction, and lake current velocity. The HPAB concluded Phase 1 by recommending that the Commission proceed with analysis of these risk factors on the incidence of protozoan acute gastrointestinal illnesses (cryptosporidiosis and giardiasis) (International Joint Commission Health Professionals Advisory Board 2017a).

Phase 2 incorporated data from Phase 1 into a time series analysis of the relationship between different types of extreme precipitation events on both drinking source water quality and human AGI. Cases of cryptosporidiosis and giardiasis were collected as human health outcomes, given prior evidence that environmental factors affect the risk of these diseases (Curriero et al. 2001; Thomas et al. 2006). All four cities consistently monitor for two water quality indicators (total coliforms and turbidity) to sufficiently allow for analysis of trends with the AGI data. Environmental and meteorological data and lake current velocity (speed and direction) were tested for inclusion in a statistical time series analysis of the relationship between different event types on both water quality and human illness.

Similar studies, including one by Chhetri and colleagues (2017), investigated the relationship between cryptosporidiosis and giardiasis, extreme precipitation, raw water turbidity, and changing weather patterns in the drinking water system of Metro Vancouver, British Columbia, Canada. The study identified a significant increase in cryptosporidiosis and giardiasis cases four to six weeks after extreme precipitation events. Our work used a similar approach, applying distributed lag nonlinear regression models to examine how precipitation and drinking water indicators were associated with AGI case counts in each of the four cities on the shores of the Great Lakes.

2.0 Methods

2.1 Study locations, design and data

This study included two cities in Canada on Lake Ontario—Hamilton and Toronto, Ontario—and two US cities on Lake Michigan—Green Bay and Milwaukee, Wisconsin. The study areas were defined by the cities' water utility service areas, including the city, retail and wholesale water customers in surrounding municipalities. The water utilities included in this study are the Green Bay Water Utility, Hamilton Water, Milwaukee Water Works and Toronto Water. Maps of each of the water utility service areas and tables of AGI cases, incidence and population by the postal codes (Forward Sortation Areas (FSAs) and ZIP codes) included in our analyses can be found in **Appendix 6.2**.

The population for each water utility service area is found in **Figure 2-1** below. Population data were obtained in 2018 from Statistics Canada and the US Census Bureau for the FSAs and ZIP codes, respectively, within the water utility service areas where AGI cases were reported during the study period of January 1, 2009 through August 31, 2014 (five years and eight months).

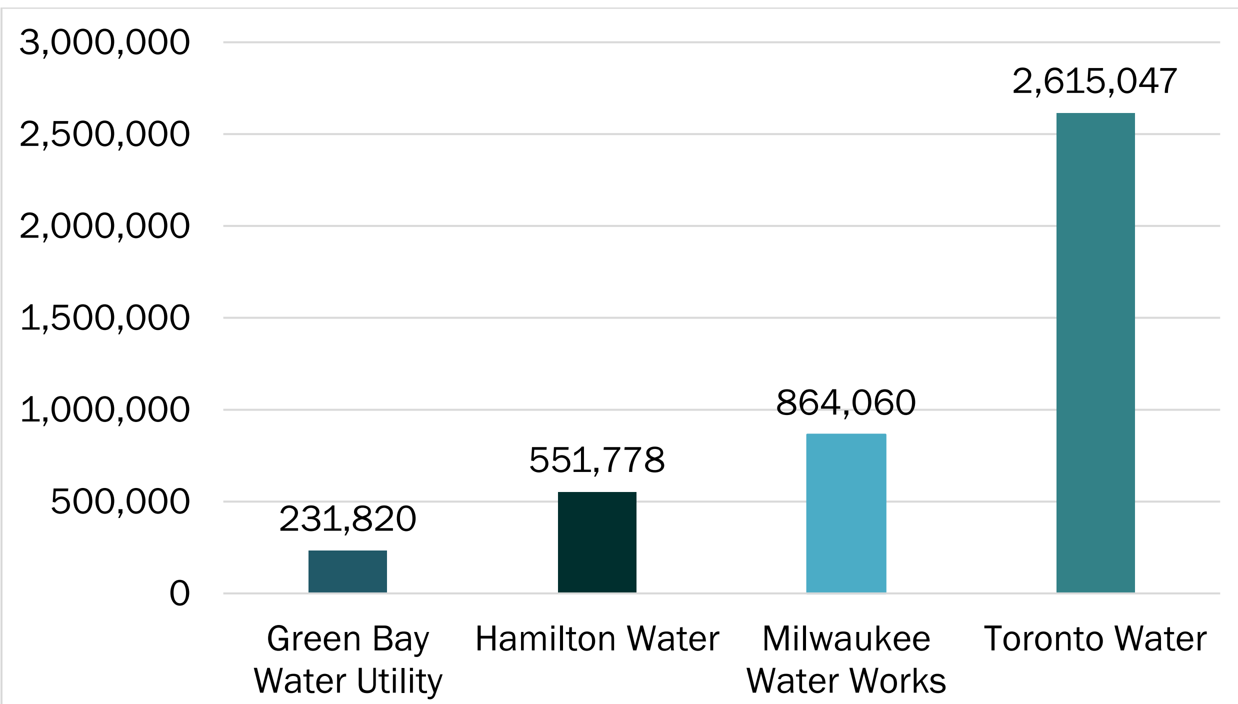

Figure 2-1: Population of the study areas (Statistics Canada 2018; US Census Bureau 2018).

Climate and weather data were obtained from the National Oceanic and Atmospheric Administration and Environment and Climate Change Canada web data portals for the nearest weather station to each city (**Table 2-1**). All four cities have a climate classification of Dfb (humid continental climate) by the Köppen-Geiger system (Kottek et al. 2006) and have similar mean annual temperatures and precipitation amounts. The range of mean annual temperature is 4.6 degrees Celsius (8.5 degrees Fahrenheit) from 8.4 degrees Celsius (47.0 degrees Fahrenheit) in Hamilton to 13.0 degrees Celsius (55.5 degrees Fahrenheit) in Milwaukee and the range of mean annual precipitation is 134 millimeters (5.28 inches) from 750 millimeters (29.53 inches) in Green Bay to 884 millimeters (34.81 inches) in Milwaukee.

Table 2-1. Summary of cities' climate and weather station locations.

Case city	Green Bay, WI	Hamilton, ON	Milwaukee, WI	Toronto, ON
Köppen-Geiger climate classification	Dfb (humid continental climate)	Dfb	Dfb	Dfb
Weather station name	Kewaunee, WI	Hamilton A	Milwaukee Mitchell International Airport	Toronto East York Dustan
Weather station location (decimal degrees)	44.462, -87.504	43.167, -79.933	42.955, -87.904	43.7, -79.34
Elevation	180.7 m (592.8 ft)	238 m (780.8 ft)	204.2 m (669.9 ft)	125 m (410.1 ft)
Mean annual temperature	12.0°C (53.5°F)	8.4°C (47.0°F)	13.0°C (55.5°F)	9.0°C (48.0°F)
Mean annual precipitation	750 mm (29.53 in)	835 mm (32.87 in)	884 mm (34.81 in)	831 mm (32.72 in)

A summary of information about the raw water intakes for each water utility is shown in **Table 2-2** (see page 7). Toronto uses four water treatment facilities and has seven active raw water intake pipes withdrawing water from Lake Ontario offshore of the Greater Toronto Area from Etobicoke to Scarborough. Hamilton has one water treatment facility and has two active raw water intake pipes in Lake Ontario. Milwaukee has two water treatment facilities and uses two active water intake pipes located offshore withdrawing water from Lake Michigan. Green Bay has one water treatment facility and uses one active water intake pipe located offshore of Kewaunee, Wisconsin, withdrawing water from Lake Michigan (see **Appendix 6.2** for maps of the approximate intake locations). Each city maintains water treatment facilities and reports on drinking water quality using results of monitoring and surveillance measures that comply with the regulatory frameworks for the respective province, state, and country (International Joint Commission Health Professionals Advisory Board 2017a).

For drinking water treatment processes, each water treatment plant follows the conventional process of coagulation and flocculation, sedimentation, filtration, disinfection and fluoridation, with some variation in the chemical inputs (see **Appendix 6.3** for details). The most notable difference between the drinking water treatment processes is that the Green Bay Water Utility and the Milwaukee Water Works both start the treatment process with ozone disinfection with the goal of destroying *Giardia* and *Cryptosporidium*, controlling taste and odor, and reducing the formation of chlorinated disinfection byproducts (e.g., halogenated trihalomethanes and haloacetic acids). Hamilton Water does not use ozone disinfection. Toronto Water only uses ozonation at its Horgan Water Treatment Plant, which started in 2013 for disinfection and taste and odor control. Toronto Water's other three water treatment plants—Clark, Harris and Island—do not use ozonation.

Table 2-2: Water utilities' drinking water treatment plants and intakes.

Water utility	Estimated number of users	Source	Drinking water treatment plant	Intake	Intake distance offshore (m)	Intake depth (m)	Drinking water treatment plant capacity		Average monthly use		Average annual use	
							m³/day	MGD	m³/day	MGD	m³	billion gallons
Green Bay Water Utility*	105,000	Lake Michigan	Green Bay Water Utility Filtration Plant	North	1,829	18.3	159,000	42	67,380	17.8	24,605,000	6.5
				South (peak demand supplement)	914	8.2						
Hamilton Water**	504,000	Lake Ontario	Woodward Avenue	Pipe 1	945	8.5	909,000	240	273,000	72	99,645,000	26.3
				Pipe 3	915	8.0						
				Pipe 2	640	7.3	Non-operational					
Milwaukee Water Works†,‡	867,000	Lake Michigan	Howard Avenue	Texas Avenue	4,000	18	1,362,000	360	390,000	103	113,133,000	29.9
			Linnwood Avenue	Linnwood Avenue	2,000	18						
Toronto Water⁺	3,200,000	Lake Ontario	R. L. Clark	1	1,610	18	615,000	162	415,000	110	151,475,000	40.0
			R. C. Harris	Northeast	2,232	15	950,000	251	168,000	44	61,365,000	16.2
				Southwest	2,125	15						
			F. J. Horgan	1	2,925	18	570,000	151	359,000	95	131,035,000	34.6
			Island	East	4,848	83	410,000	108	176,000	46	62,240,000	16.4
				Middle	4,662	83						
				West	4,696	83						
				Shallow - West	828	11	Not in service					
				Shallow - East	690	17						

Units: m = meters; m³ = = meters cubed; m³/day = meters cubed per day; MGD = million gallons per day
* Green Bay Water Utility 2014; Personal communication with Russ Hardwick.
** Halton-Hamilton Source Protection Committee 2015.
† Milwaukee Water Works 2017.
‡ City of Milwaukee 2015.
⁺ Credit Valley, Toronto and Region and Central Lake Ontario Source Protection Committee 2015.

An ecological time series study design was used to assess the relationship between reported cases of cryptosporidiosis and giardiasis in the population served by their respective water utilities and the following environmental factors:

- extreme precipitation event (greater than or equal to a 90th percentile precipitation)
- precipitation patterns (dry periods or wet periods)
- air and water temperature
- raw water quality indicators of turbidity and total coliforms
- lake current direction (onshore or offshore) near the location of the water intakes

Health, environmental and water quality indicator data were acquired as previously described (International Joint Commission Health Professionals Advisory Board 2017a) and are shown in **Table 2-3**. Disease incidence data were acquired and reported for all four cities, but data on possible confounding risk factors were more limited. These data collected by public health workers during outbreak investigations include other recognized potential confounding risk factors for the same infection—e.g., occupations with an increased risk of exposure (e.g., agriculture, childcare), travel to locations where infections are endemic, and recreational activities like camping, swimming and petting zoos. However, because some health departments only perform detailed investigations of risk factors for cases thought to be part of an ongoing outbreak, these confounding factors are not available for cases of sporadic illness. Also, access to these data were dependent upon when public health authorities switched from paper to electronic data records and investigators' effective lack of access to paper records. As a result, these potentially confounding factors were not included in this Phase 2 analysis.

Table 2-3: Health, climate and environmental data requested during Phase 1 of this study. The subset of data that was analyzed in Phase 2, based on availability from all four cities during the study period, have their cells highlighted in teal.

Environmental data: weather/meteorology	Biological hazards of source water indicators	Health risk factors	Acute gastrointestinal illnesses
Precipitation*	Turbidity**	Travel history	Reported cases of giardiasis
Extreme rain events*	Total coliforms**	Use of bottled water	Reported cases cryptosporidiosis
Temperature – air* and water	*Escherichia coli***	Recreational water exposure	
Lake current direction and speed	*Cryptosporidium parvum***	Day care center use	
Combined sewer overflow events	*Giardia lamblia***		
	Nitrates**		

* Chhetri et al. 2017
** International Joint Commission Health Professionals Advisory Board 2014

To compare the geographic distribution of the health data with the cities' water utility service areas, water service area maps were obtained for each of the water utilities (see **Appendix 6.2**). These maps show that several municipalities purchase wholesale potable water from the water utility in areas where health data were not obtained for this study. Future studies should incorporate the health data from the entire service areas to enable a comprehensive analysis.

Raw water quality data for turbidity and total coliforms were available for each water treatment plant and were included in our statistical analysis. Other raw water quality indicators were not consistently available from all four cities' water utilities and were omitted from this analysis, including *Escherichia coli*, *Cryptosporidium parvum*, *Giardia lamblia*, and nitrates. Dependent variables included laboratory-confirmed cases of cryptosporidiosis and giardiasis in each city's water utility service area. Independent variables included precipitation, air temperature, raw water temperature, raw water turbidity and raw water total coliforms.

Precipitation was aggregated to seven-day cumulative values. Snowfall was converted to its liquid water equivalent according to the formula:

$$(snowfall\ [mm] \div 10)\ = liquid\ water\ equivalent\ (mm)$$

Cumulative precipitation was the sum of rainfall (mm) and snowfall's liquid water equivalent (mm). Air temperature was aggregated to a three-week trailing mean. Raw water temperature, turbidity and total coliforms were aggregated to seven-day mean values.

Extreme precipitation events were defined as those meeting or exceeding the 90th percentile of the weekly precipitation distribution across the study period. Use of the 90th percentile cutoff was based on expected increases in source water microbial loads following extreme events (Bush et al. 2014; Curriero et al. 2001; Kistemann et al. 2002).

Additionally, we defined precipitation pattern (dry or wet periods) to enable analysis of occurrences of an extreme precipitation event directly following a dry period (e.g., an 'abrupt precipitation spike'). To be consistent with the methods used by Chhetri and colleagues (2017), we sought to replicate Vancouver's even split of dry weeks and wet weeks. Because the climate classification for these four Great Lakes cities (Dfb: snow, fully humid, warm summer) is different than Vancouver's climate classification (Csb: warm temperate, summer dry, warm summer in Kottek et al. 2006), the definition of precipitation pattern (dry or wet periods) used in this study was determined by the weather data for each of the case cities. The best fit for each city was to define Green Bay and Milwaukee as less than or equal to 40 days of no precipitation in the preceding 60 days as dry and Hamilton and Toronto as less than or equal to 35 days of no precipitation in the preceding 60 days as dry. See **Appendix 6.5** for more details.

Weekly measures of raw water indicator data for turbidity (Nephelometric Turbidity Units) and total coliforms (coliform forming units) were calculated as the seven-day average of their respective measurement unit. Modelled weekly lake current data at a depth of 10 meters for locations near each water treatment plant intake were obtained from the National Ocean and Atmospheric Administration. Using this information, a weekly lake current onshore/offshore factor was calculated and included in the modeling exercise.

Geocoding and spatial data analysis was performed using ArcGIS.[1] The cumulative cryptosporidiosis and giardiasis cases reported per week and patients' postal codes (FSA or ZIP code) were used to create maps of AGI cases and incidence per 10,000 residents for each water utility service area. Postal code polygons were downloaded from publicly available Canadian and Wisconsin government data.[2] Cases were assigned to the specific postal code polygons based on the patient's reported postal code. Incidence (per 10,000 residents) was calculated according to the formula:

$$(cases \div population) \times 10{,}000$$

This study was approved by the research ethics boards at Simon Fraser University (Simon Fraser, British Columbia), the Medical College of Wisconsin (Milwaukee, Wisconsin), and Denver Public Health (Denver, Colorado).

2.2 Statistical analysis

The spatial distribution of AGI cases was analyzed using Pearson's Chi-squared (χ^2) goodness of fit tests to determine if the reported numbers of AGI cases across the postal codes of each water utility service area were different than the expected number of AGI cases based on the population of each postal code.

The association between the dependent variables (combined cryptosporidiosis and giardiasis cases) and independent variables (precipitation, precipitation pattern, raw water turbidity and total coliforms and lake current velocity) were tested using a distributed lag nonlinear regression models with a Poisson outcome. Model parameters accounted for air and raw water temperature, precipitation pattern (dry or wet periods), seasonality in cryptosporidiosis and giardiasis, and the effects of time and public holiday impacts on healthcare reporting and access, as described by Chhetri and colleagues (2017).

The population attributable risk is reported as an estimate of the proportion of combined cryptosporidiosis and giardiasis cases in the population that is attributable to extreme precipitation. relative risk is approximated from population attributable risk using the relationship:

$population\ attributable\ risk\ = \left(\frac{relative\ risk\ -1}{relative\ risk}\right) \times 100\%$ (Gasparrini and Leone, 2014)

Numerous models were fitted using quasi-maximum likelihood to select covariates (e.g., temperature, turbidity, total coliforms and lake currents) and modeling parameters (e.g., degrees of freedom for spline functions). The best fitting model was determined using the quasi-Akaike's information criterion (qAIC) goodness-of-fit statistic (Gasparrini 2011).[3]

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[1] Environmental Systems Research Institute ArcGIS version 10.6.1, Redlands, California, United States.
[2] Data were downloaded from ArcGIS Online. Available from: arcgis.com.
[3] Statistical analyses were performed using Microsoft Excel, R (R Core Team, v.3.5.3, 2018) and RStudio software using disturbed lag nonlinear regression model package dlnm.

3.0 Results and Discussion

3.1 AGI spatial distribution

The number of laboratory-confirmed cases of cryptosporidiosis and giardiasis within each water utility service area is shown in **Figure 3-1** below. The combined AGI cases (cryptosporidiosis and giardiasis) for each water utility service area during the study period of January 1, 2009 through August 31, 2014 (five years and eight months) were:

- Green Bay Water Utility: 192
- Milwaukee Water Works: 699
- Hamilton Water: 301
- Toronto Water: 2,599

Correspondingly, residents of the Green Bay Water Utility service area had the highest incidence of cryptosporidiosis (4.27 cases per 10,000 residents). Residents of the Toronto Water utility service area had the highest incidence of giardiasis (8.84 cases per 10,000 residents) and highest incidence of combined AGI (9.94 cases per 10,000 residents). Residents of the Hamilton Water utility service area had the lowest incidence of combined AGI (5.46 per 10,000 residents).

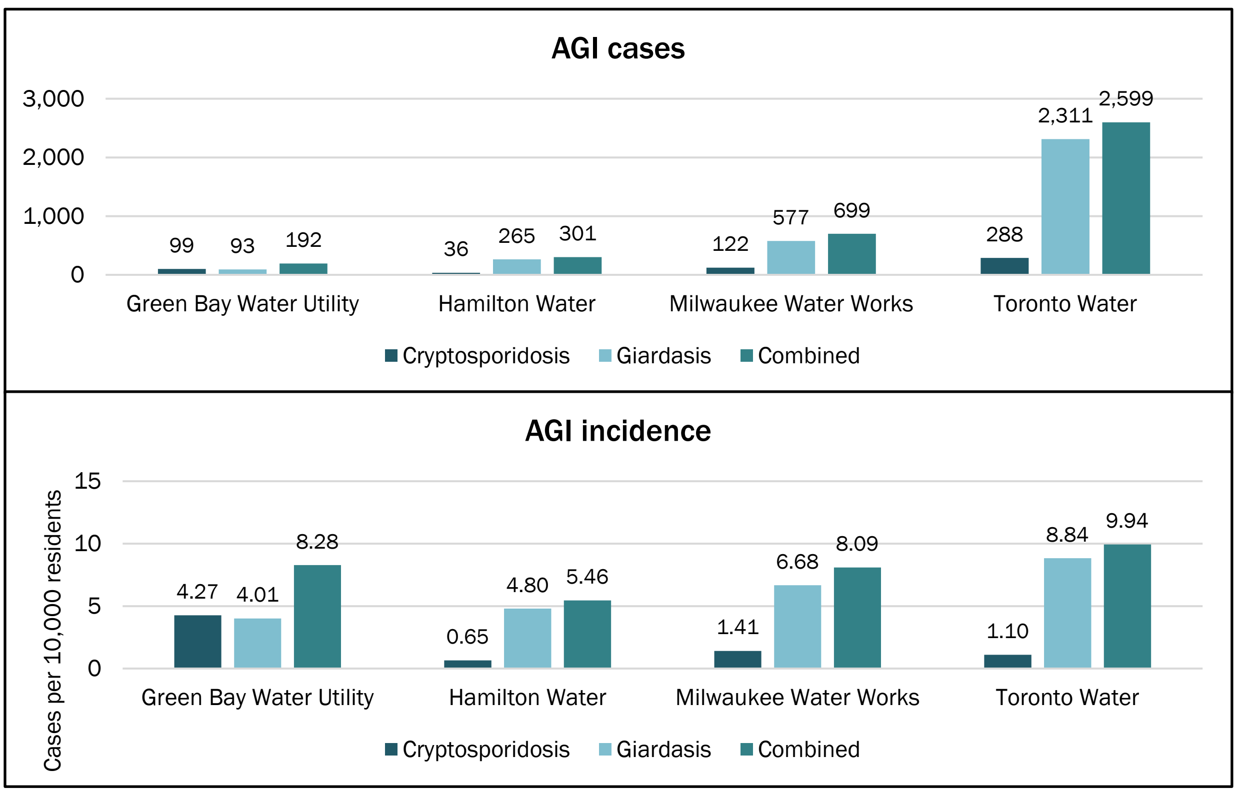

Figure 3-1: Top: AGI cases (cryptosporidiosis and giardiasis), and Bottom: AGI incidence per 10,000 residents, both during the study period of January 1, 2009 through August 31, 2014.

The distribution of weekly combined AGI cases displayed by month for each water utility service area is shown in **Figure 3-2** (below on page 14). The number of weekly combined AGI cases ranged from zero to six for Green Bay and Hamilton, zero to 10 for Milwaukee, and one to 20 for Toronto. The highest number of weekly combined AGI cases were from July to September, which is consistent with the seasonality of AGI cases of residents within the metro Vancouver drinking water service area (Chhetri et al. 2017) as well as the seasonality of AGI cases across Ontario (Greig et al. 2001; Public Health Ontario 2020) and Wisconsin (Wisconsin Department of Health Services 2018). See **Appendix 6.4** for additional figures showing the seasonality of AGI cases.

Maps of combined AGI incidence by postal code are shown in **Figure 3-3** (below on page 15), and maps of incidence of each disease by postal code are in **Appendix 6.2**. Upon analyzing the spatial distribution of AGI cases across the postal codes of each water utility service area using Pearson's Chi-square (χ^2) goodness of fit tests, disproportionate amounts of AGI cases across the postal codes were revealed in each water utility service area except for the Green Bay Water Utility. In the Hamilton Water, Milwaukee Water Works, and Toronto Water utility service areas, certain postal codes have more AGI cases than an expected distribution of cases proportional to the population of the postal codes (**Table 3-1**).

Table 3-1. Pearson's Chi-squared results for distribution of AGI cases across postal codes.

AGI cases across postal codes		χ^2	df	*p*-value
Green Bay	Combined AGI	9.8	9	0.3635
	Cryptosporidiosis	8.2	9	0.5138
	Giardiasis	11.0	9	0.2749
Hamilton	Combined AGI	57.4	20	<0.0001*
	Cryptosporidiosis	21.3	20	0.3797
	Giardiasis	56.4	20	<0.0001*
Milwaukee	Combined AGI	516.3	31	<0.00001*
	Cryptosporidiosis	56.8	31	0.0031*
	Giardiasis	614.9	31	<0.00001*
Toronto	Combined AGI	1333.1	95	<0.00001*
	Cryptosporidiosis	167.3	95	<0.00001*
	Giardiasis	1282.1	95	<0.00001*

χ^2 = Pearson's Chi-squared results; df = degrees of freedom
*significant at the $p<0.01$ level

The water utilities with multiple intakes per water treatment plant—Green Bay Water Utility, Hamilton Water, and Toronto Water's Harris and Island water treatment plants—mix the raw water in the treatment plant. The managers of the water utilities with multiple water treatment plants—Milwaukee Water Works (2 plants) and Toronto Water (4 plants)—reported that their treated water is mixed within their distribution systems in different ways over time. For these reasons, it is not possible to assign delivery of the treated water from a particular intake or water treatment plant to a particular postal code or customer's address. Furthermore, people likely obtain water from many different locations throughout the day (e.g., from taps and water fountains at work, school, daycare facilities and restaurants, as well as bottled beverages). However, this study's premise ties these illness trends with the impacts of precipitation on residential drinking water. While exposure to these diseases is possible from food or drinking water consumed at other locations, many people work and attend school within their respective metro areas, which are served by the same water utility.

The numbers of cases reported here for colder 'nonswimming' months show that recreational exposures are an unlikely source. It is true that infected persons are not only drinking water from their residence, but that fact would bias towards null results, so this is very likely a residential drinking water source. Incidence of these illnesses was also noted during cold seasons where outdoor recreational activities such as camping and swimming are less likely sources of exposure, and seasonality was accounted for in the modeling exercises for each city. Further examination of the observed spatial variation in disease incidence is warranted to answers questions regarding variability in risk from finished water distribution.

Precipitation trends were analyzed in this study. Box plots of cumulative weekly precipitation, grouped by month, for each city are shown in **Figure 3-4** (below on page 16). The blue line indicates the 90th percentile weekly cumulative precipitation, which is the definition we used for an extreme precipitation event. The dots represent weekly cumulative precipitation datapoint, and every dot above the blue line is an extreme precipitation week. The number of instances of extreme precipitation events following a dry period (e.g., abrupt precipitation spikes) are shown in tables for each case city listing the extreme precipitation event weeks in **Appendix 6.5**

... it is not possible to assign delivery of the treated water from a particular intake or water treatment plant to a particular postal code or customer's address... [but] while exposure to these diseases is possible from food or drinking water consumed at other locations, many people work and attend school within their respective metro areas, which are served by the same water utility.

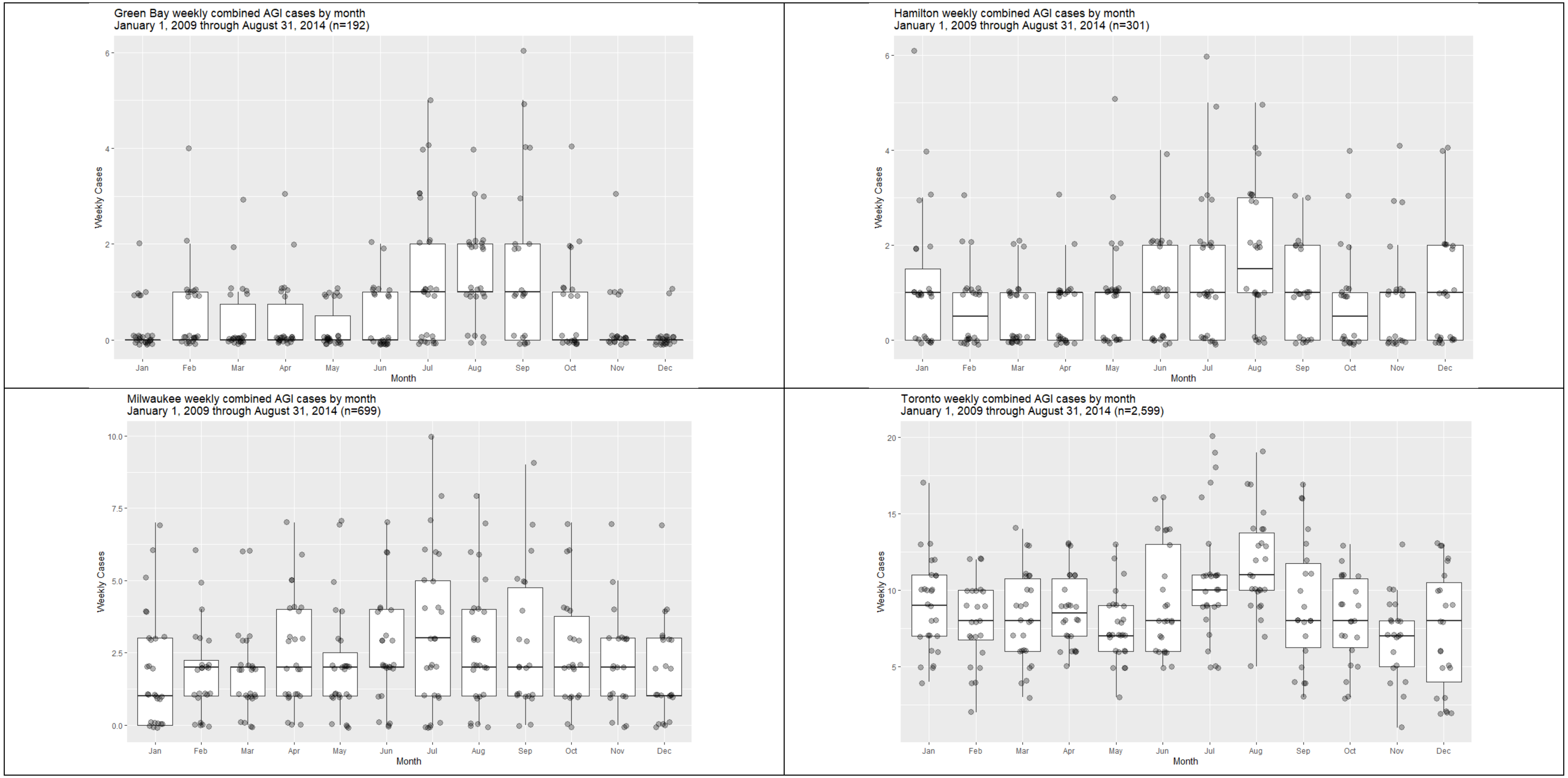

Figure 3-2: Boxplots of weekly combined AGI cases, grouped by month, for the four case cities. The upper whisker extends from the hinge to the highest value that is 1.5 times the interquartile range of the hinge. Dots represent weekly data points.

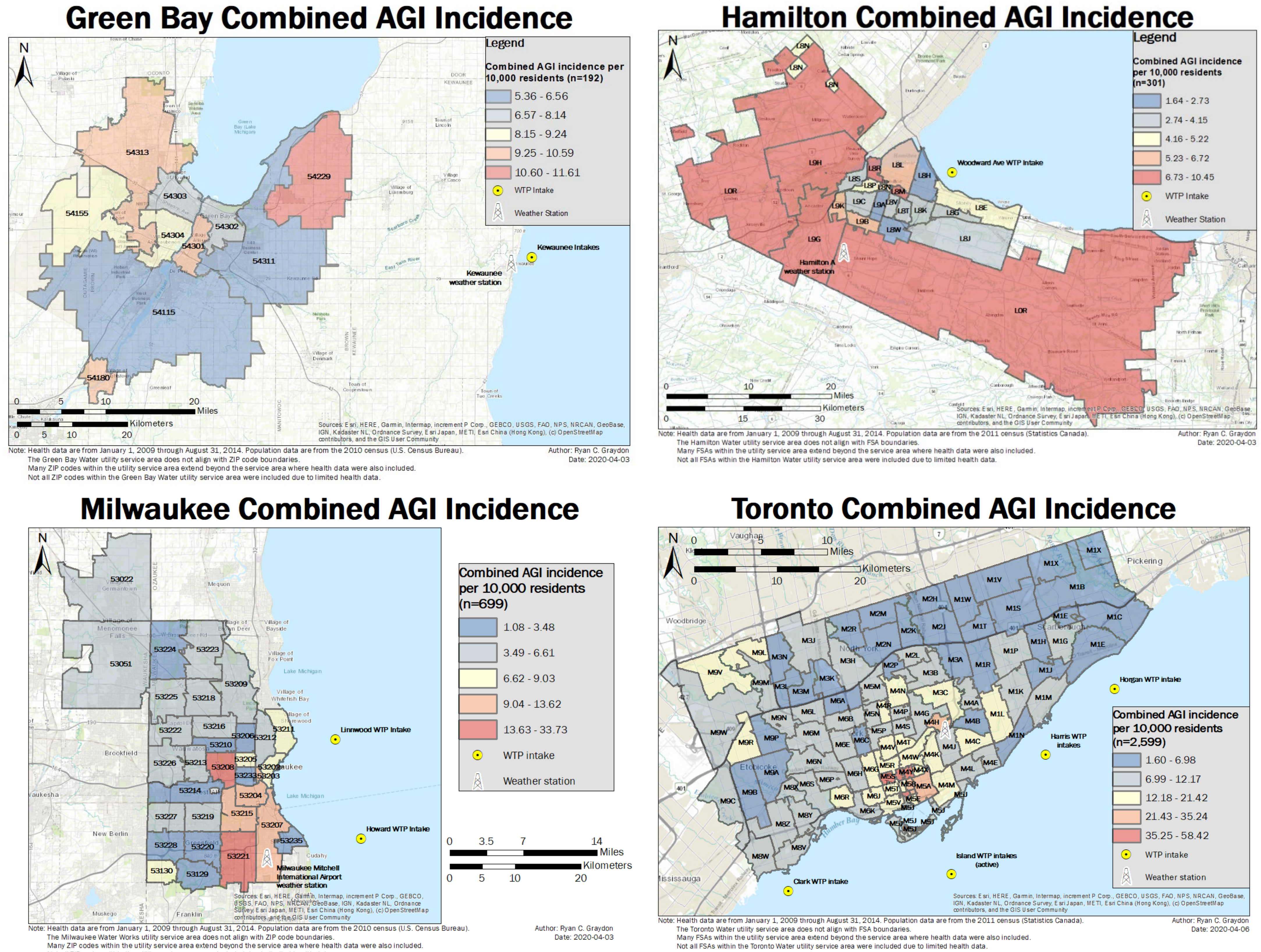

Figure 3-3: Maps of combined AGI incidence per 10,000 residents for each city by respective FSA or ZIP code.

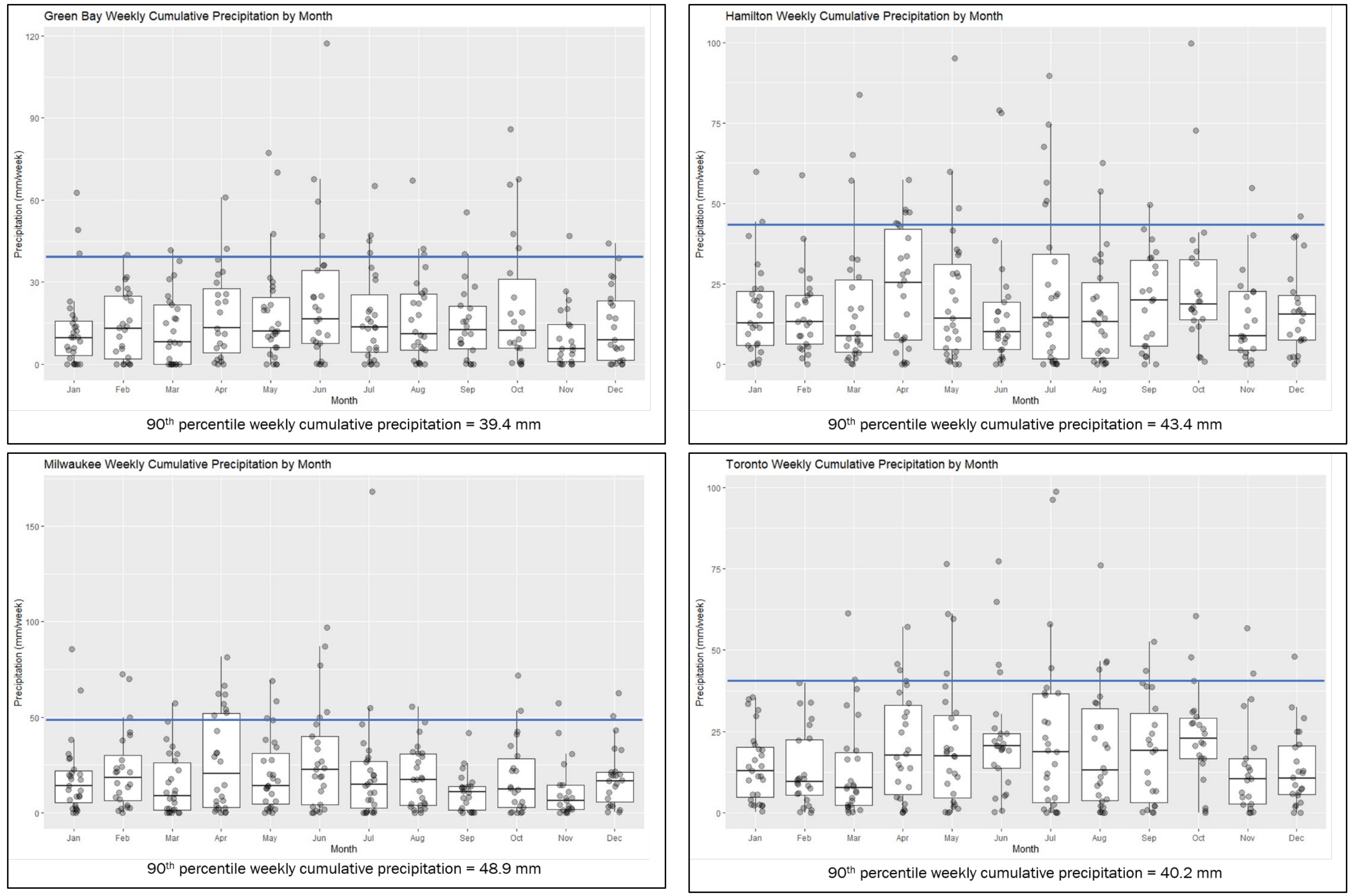

Figure 3-4: Boxplots of weekly cumulative precipitation, grouped by month, for the four case cities. The upper whisker extends from the hinge to the highest value that is within 1.5 interquartile range of the hinge. Dots represent weekly data points.

3.2 Model analysis

Models were developed individually for each utility's drinking water treatment plant to incorporate the water quality indicators measured at the utility's raw water intakes and examine the relationship between weather (extreme precipitation and precipitation pattern), raw water quality indicators, and the cases for both cryptosporidiosis and giardiasis combined. A regression analysis among the raw water quality indicators and weather indicators showed no evidence of correlation, neither between the indicators themselves nor between raw water quality indicators and weather indicators.

Air temperature (three-week trailing average), water temperature (weekly average) and lake current velocity (speed, direction and onshore/offshore factor) did not improve model fit and were dropped from the final model.

The model with the best fit for most water treatment plants included variables for combined AGI cases, holiday weeks, cumulative precipitation and precipitation pattern (wet or dry). The addition of the raw water quality indicators turbidity and total coliforms also improved model fit for most water treatment plants (**Table 3-2**).

Table 3-2: Drinking water treatment plants' raw water quality indicators that contributed to best model fit.

Water Utility – DWTP intake	Turbidity	Total coliforms
Green Bay – Kewaunee	Yes	Yes
Hamilton – Hamilton	Yes	Yes
Milwaukee – Howard	Yes	No
Milwaukee – Linnwood	Yes	No
Toronto – Clark	Yes	Yes
Toronto – Harris	Yes	Yes
Toronto – Horgan	Yes	No
Toronto – Island	Yes	Yes

There was some variation in the model results for Toronto and Milwaukee, which have multiple drinking water treatment plants (DWTPs) resulting in multiple streams of data being tested. The model covariate turbidity improved the models results for both of Milwaukee Water Works' DWTPs and for all four of Toronto Water's DWTPs. However, when the model covariate total coliforms was added, the model fit for both of Milwaukee Water Works' DWTPs declined but the model fit for three of Toronto Water's four DWTPs improved fit while the model fit for Toronto Water's Horgan DWTP also declined. See **Appendix 6.6** for more details.

These results indicate that source water quality indicators at raw water intakes, as recommended by the IJC (International Joint Commission Health Professionals Advisory Board 2014), also prove useful for public health research.

Using the model with the best fit to the data for each water treatment plant, the population attributable risk of AGI following an abrupt precipitation spike was calculated and displayed in **Figure 3-5** and **Figure 3-6** (below on pages 19 and 20, respectively). For Green Bay, there was no statistically significant change to the population attributable risk following abrupt spikes in precipitation. This may be due to Green Bay having the fewest AGI cases (n=192) relative to the other more populous cities and thus low statistical power to detect an effect. Notably, Green Bay is the only one of these four case cities that has a separate sanitary sewer system instead of a combined sewer system. However, information about sewer overflow events, whether from sanitary sewer overflows in Green Bay or combined sewer overflows in the other three case cities, was not provided in response to our requests for information from the cities. See **Appendix 6.1** for the list of information requested.

Results for relative risk showed Hamilton with an increase in relative risk three to six weeks following an abrupt precipitation spike. There was a peak in relative risk three to six weeks after abrupt precipitation spikes for Milwaukee's two models that did not reach statistical significance (**Figure 3-5** below on page 19). An increase in relative risk one week after an abrupt precipitation spike was seen in Toronto's four models, but only the model for Toronto Island was statistically significant (**Figure 3-6** below on page 20).

The increase in relative risk three to six weeks after this spike is consistent with the findings by Chhetri and colleagues (2017) who found an increased relative risk for AGI four to six weeks after abrupt precipitation spikes in Vancouver, British Columbia.

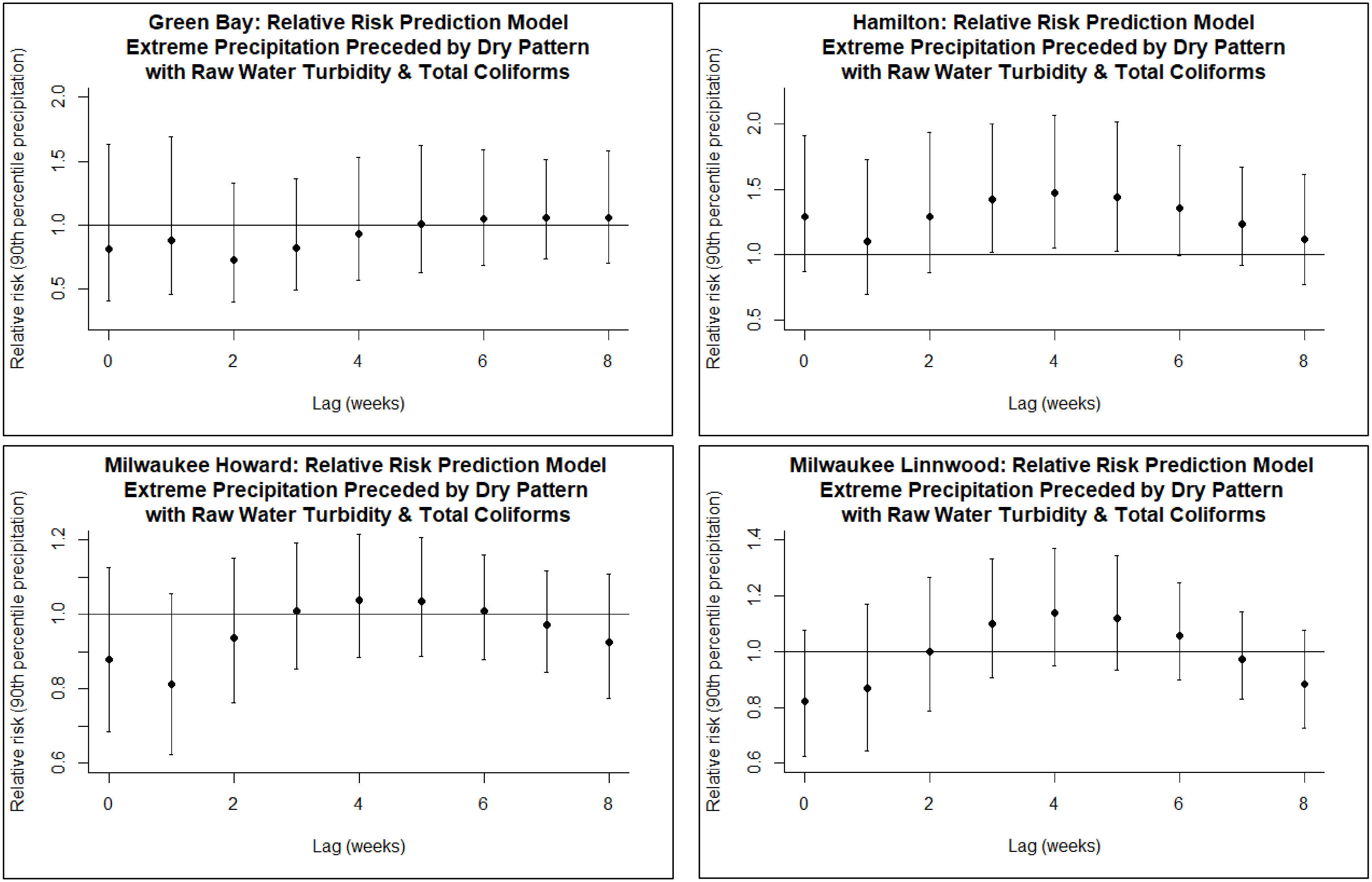

Figure 3-5: Relative risk of AGI (cryptosporidiosis and giardiasis) following extreme precipitation (≥90th percentile precipitation event) preceded by a dry period for Green Bay, Hamilton and Milwaukee's drinking water treatment plants

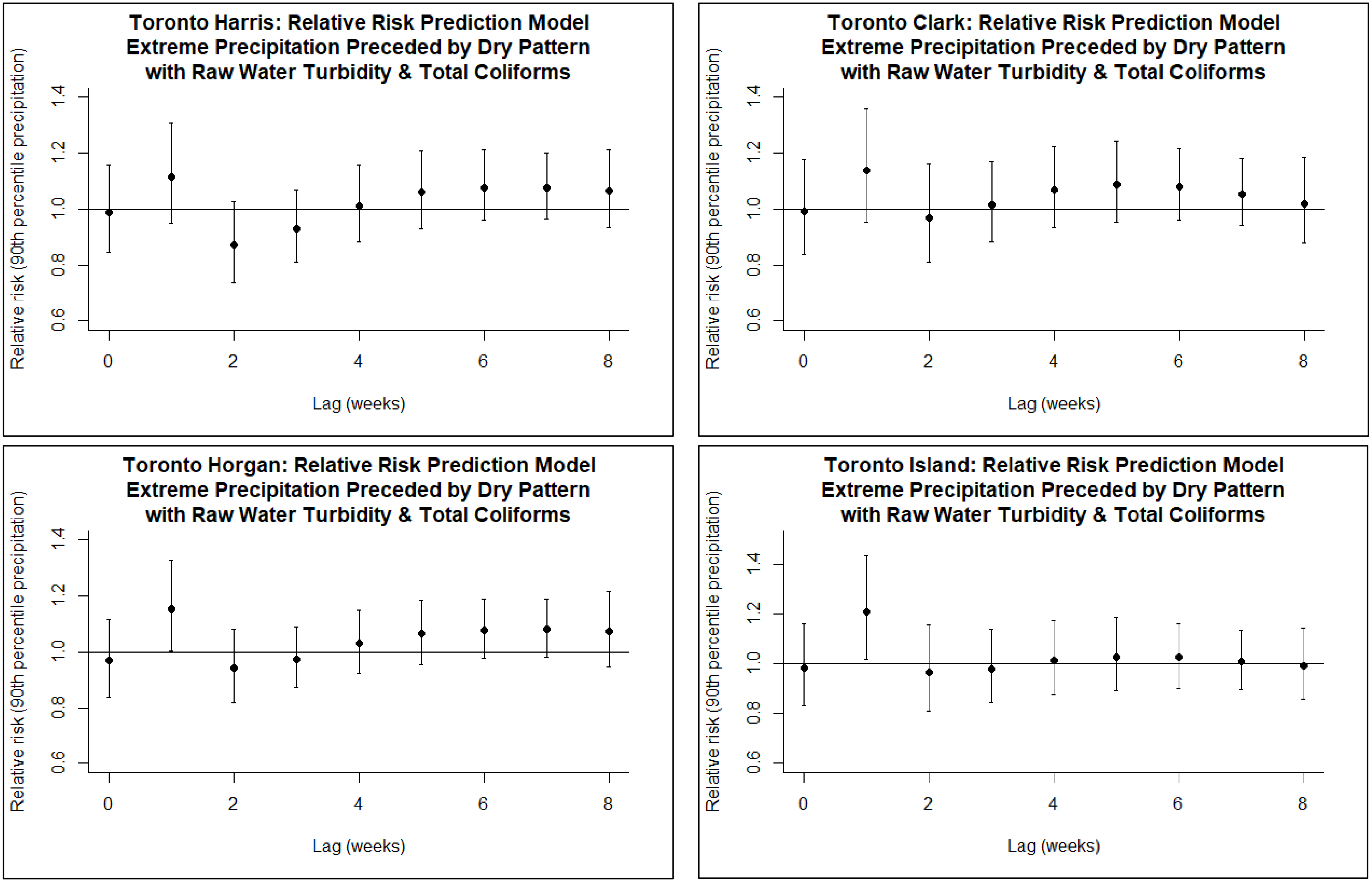

Figure 3-6: Relative risk of AGI (cryptosporidiosis and giardiasis) following extreme precipitation (≥90th percentile precipitation event) preceded by a dry period for Toronto Water's drinking water treatment plants.

4.0 Findings and Recommendations

This work demonstrated that integrated comparable binational environmental and human health data can be obtained and used for research and modeling to inform the protection of overall human health in the Great Lakes.

While other studies have noted that incidence of cryptosporidiosis and giardiasis are sensitive to rain events (Britton et al. 2010; Lake et al. 2005; Lal et al. 2013), this is the first study to our knowledge that has examined source water, as measured at drinking water intakes along with precipitation on risk of AGI. These results emphasize that source water monitoring and reporting continues to be of vital importance to understand the risks faced by those reliant on the Great Lakes for their water supply. The governments of Canada and the United States currently only report on finished water quality in the triennial State of the Great Lakes reports as part of their responsibilities under the Great Lakes Water Quality Agreement (Canada and the United States, 2017). This study indicates that monitoring and surveillance for indicators of source water quality is also critical to assessing whether the Great Lakes remain swimmable, fishable and, in this case, drinkable.

The increased risk of AGI following extreme rainfall was found for three of four large cities studied in Canada and the United States for two of the Laurentian Great Lakes—Lake Michigan and Lake Ontario—similar to impacts that have been reported for cities in other climatological environments.

Key findings from this work include:

1. The relative risk of AGI three to six weeks after extreme precipitation (greater than or equal to the 90th percentile precipitation event) preceded by a dry period was significantly greater for Hamilton. Milwaukee showed a similar pattern but the elevation in risk was not statistically significant.
2. This work also demonstrates that the addition of turbidity and total coliforms improves the fit of the model to the observed data (based on the qAIC statistic) in many cases, and that improvement in model fit varied based on which intake data was used. Turbidity had the largest impact on improving the fit, though the inclusion of total coliforms also proved useful.

These case studies were done to assess the feasibility of using binational databases for the assessment of AGI risk from drinking water sourced from Great Lakes surface waters in relation to extreme precipitation events. It revealed that such an analysis is possible, despite the limitations of data access, availability and harmonization as barriers (Bassil et al. 2015). Health data access was particularly challenging. Despite long-standing environmental monitoring programs in both countries, much of the environmental data for this study had to be assembled from a combination of national, state or municipal entities. In each country and binationally, to our knowledge, no clearinghouse exists for water quality data for the sources of drinking water. We did not examine the impact of changes in relative contributions from multi source water systems like Toronto and Milwaukee (e.g., comparing the risk of waterborne illness from one treatment plant compared with another). Such an analysis may be challenging due the mixing of sources in the systems but could provide additional insights into drivers of increased AGI risk.

The increasing availability of digital data from public health outbreak investigations may allow additional confounding risk factors to be included in large-scale analyses in the future. Additional data and detail could also help explain the variation in lag time for peak risk for each city. Potential explanatory factors are variation in the time between testing and reporting and perhaps differences in health access, culturally based response to illness and diagnostic delays.

In evaluating future risk, the IJC should consider the potential implications of climate change on precipitation patterns in the Great Lakes into the 2080s. As shown in **Figure 4-1** (below) most models predict significantly wetter summers and slightly drier winters (Byun et al. 2019). An analysis by Chhetri and colleagues (2019) in three temperate rainforest watersheds serving Vancouver, British Columbia, estimated a 16 percent increase in AGI cases with increases in winter precipitation. Modeling of future dry to wet periods is more challenging.

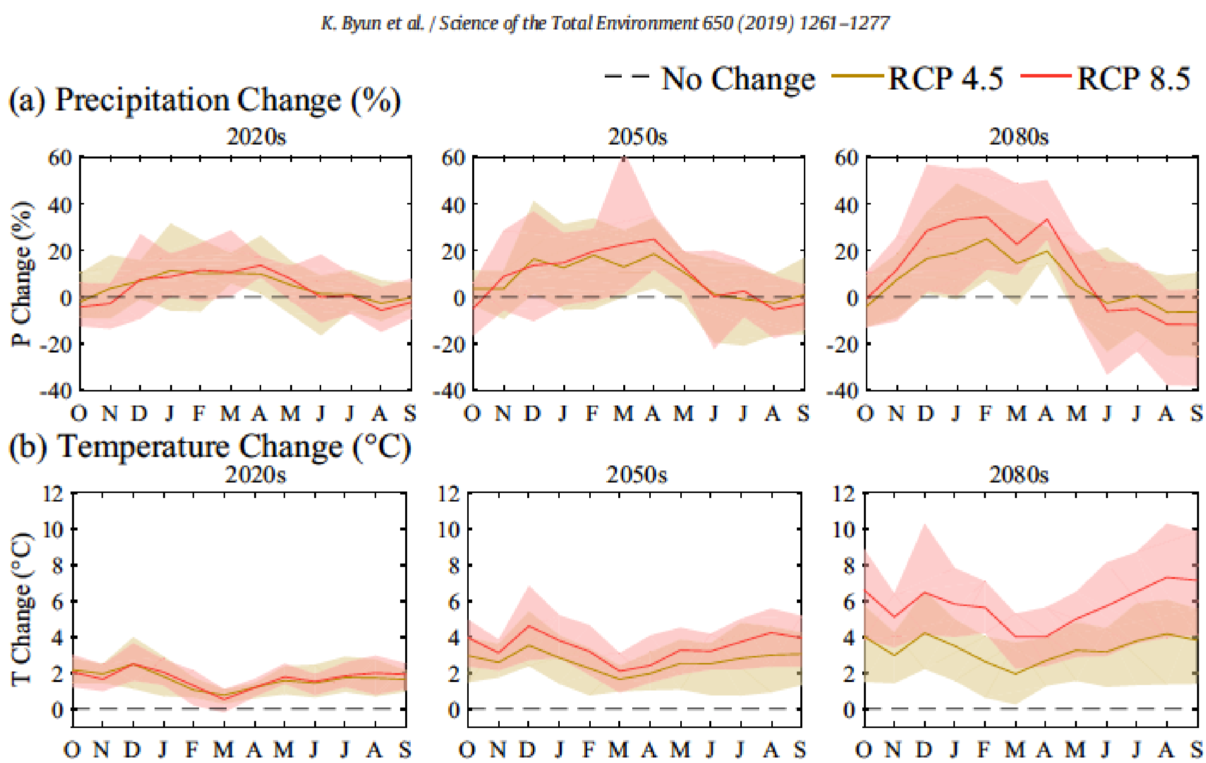

Figure 4-1: Projected monthly changes in precipitation and air temperature in the Great Lakes region of the United States. Climate modeling of the Great Lakes region of the United States predict increasing winter and spring precipitation and slight decrease in summer precipitation patterns towards the 2080s. This pattern is amplified in the RCP 8.5 scenario versus the RCP 4.5 scenario (Byun et al. 2019).

Following review of this work, the HPAB recommends that the Parties do the following:

- In order to confirm these findings and their applicability across the Great Lakes basin, expand this work to assess gastrointestinal illness risks for other Great Lakes and cities that source their water from the Great Lakes and its connecting channels, such as Thunder Bay (Lake Superior), Sarnia (Lake Huron), Windsor (Detroit River), London (both Lake Erie and Huron) and Mississauga (Lake Ontario) in Canada, and Duluth, Minnesota (Lake Superior), Chicago, Illinois (Lake Michigan), Saginaw, Michigan (Lake Huron), Cleveland, Ohio (Lake Erie) and Niagara Falls, New York (Niagara River) in the United States. Health data were provided through central databases at the state and provincial levels, therefore collaboration with state and provincial governments would be critical to assembling necessary data.
- Establish a binational drinking water source quality and human health clearinghouse for cities that source water from the Great Lakes. This will require developing partnerships with both municipal water systems, health data providers and existing organizations, such as the Huron to Erie Drinking Water Monitoring Network to improve source water quality and disease surveillance across the Basin.
- Include indicators of source water quality at drinking water intakes as part of their reporting for the State of the Great Lakes. Source water monitoring and reporting continues to be of vital importance in understanding the risks faced by those reliant on the Great Lakes for their water supply.
- For a future study, examine links between AGI and recreational water quality in the same four cities. This would assist with clarifying illness attribution to drinking water, if modeling results were not as conclusive for recreational waters.
- Municipalities should assess their future drinking water system vulnerabilities considering climate related changes in precipitation and temperature. These include increased runoff, turbidity and nutrient load, which impacts multiple biocontaminants including toxic algal blooms (International Joint Commission Health Professionals Advisory Board 2017b) and waterborne microorganisms.

The HPAB notes that continuation of this work should position IJC as instrumental in harmonizing source water indicators and support real progress on monitoring human health in the Great Lakes.

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6.0 Appendices

6.1 Timeline and availability for data collected from the four case cities

Table 6-1: Timeline and availability for illness, weather and environmental data. Fields highlighted in teal denote common data available over time for all locations. nd means no data. Reproduced from International Joint Commission Health Professionals Advisory Board 2017a.

Data	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Green Bay, WI-US															
Illnesses	nd	nd	nd	nd	nd	nd	●	●	●	●	●	●	●	●	●
Illness co-factor	nd	nd	nd	nd	nd	nd	●	●	●	●	●	●	●	●	●
Precipitation	●	●	●	●	●	●	●	●	●	●	●	●	●	●	nd
Wind direction/velocity	●	●	●	●	●	●	●	●	●	●	●	●	●	●	nd
Lake currents	nd	nd	nd	●	●	●	●	●	●	●	●	●	●	●	nd
Temperature (air)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	nd
Milwaukee, WI-US															
Illnesses	nd	nd	nd	nd	nd	nd	●	●	●	●	●	●	●	●	●
Illness co-factors	nd	nd	nd	nd	nd	nd	●	●	●	●	●	●	●	●	●
Precipitation	●	●	●	●	●	●	●	●	●	●	●	●	●	●	nd
Wind direction/velocity	●	●	●	●	●	●	●	●	●	●	●	●	●	●	nd
Lake currents	nd	nd	nd	●	●	●	●	●	●	●	●	●	●	●	nd
Temperature (air)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	nd
Hamilton, ON-CA															
Illnesses	●	●	●	●	●	●	●	●	●	●	●	●	nd	nd	nd
Illness co-factors	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Precipitation	nd	nd	●	●	●	●	●	●	●	●	●	●	●	●	nd
Wind direction/velocity	●	●	●	●	●	●	●	●	●	●	●	●	●	●	nd
Lake currents	nd	nd	nd	●	●	●	●	●	●	●	●	●	●	●	nd
Temperature (air)	nd	nd	●	●	●	●	●	●	●	●	●	●	●	●	nd
Toronto, ON-CA															
Illnesses	●	●	●	●	●	●	●	●	●	●	●	●	nd	nd	nd
Illness co-factors	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Precipitation	●	●	●	●	●	●	●	●	●	●	●	●	●	●	nd
Wind direction/velocity	●	●	●	●	●	●	●	●	●	●	●	●	●	●	nd
Lake currents	nd	nd	nd	●	●	●	●	●	●	●	●	●	●	●	nd
Temperature (air)	●	●	●	●	●	●	●	●	●	●	●	●	●	●	nd

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Table 6-2: Timeline and availability for water quality indicators and combined sewer overflow data. Fields highlighted in teal denote common data available over time for all locations. nd means no data. Reproduced from International Joint Commission Health Professionals Advisory Board 2017a.

Data	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Green Bay, WI-US															
Turbidity	nd	●	●	●	●	●	●	●	●	●	●	●	●	nd	nd
Nitrate	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
E. coli	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	●	●	nd
Total coliform	nd	●	●	●	●	●	●	●	●	●	●	●	●	●	nd
C. parvum	nd	●	●	●	●	●	●	●	●	●	●	●	●	●	nd
Giardia lamblia	nd	●	●	●	●	●	●	●	●	●	●	●	●	●	nd
Sewerage overflow events – city does not use combined sewer															
Milwaukee, WI-US															
Turbidity	nd	●	●	●	●	●	●	●	●	●	●	●	●	●	nd
Nitrate	nd	●	●	●	●	●	●	●	●	●	●	●	●	●	nd
E. coli	nd	●	●	●	●	●	●	●	●	●	●	●	●	●	nd
Total coliform	nd	●	●	●	●	●	●	●	●	●	●	●	●	●	nd
C. parvum	nd	●	●	●	●	●	●	●	●	●	●	●	●	●	nd
Giardia lamblia	nd	●	●	●	●	●	●	●	●	●	●	●	●	●	nd
Sewerage overflow events	●	●	●	●	●	●	●	●	●	●	●	●	●	●	nd
Hamilton, ON-CA															
Turbidity	nd	●	●	●	●	●	●	●	●	●	●	●	●	●	nd
Nitrate	nd	●	●	●	●	●	●	●	●	●	●	●	●	●	nd
E. coli	nd	●	●	●	●	●	●	●	●	●	●	●	●	●	nd
Total coliform	nd	●	●	●	●	●	●	●	●	●	●	●	●	●	nd
C. parvum – not tested	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Giardia lamblia – not tested	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Sewerage overflow events	nd	nd	nd	●	●	●	●	●	●	●	●	●	●	●	nd
Toronto, ON-CA															
Turbidity	nd	●	●	●	●	●	●	●	●	●	●	●	●	●	nd
Nitrate	●	●	●	●	●	●	●	●	●	●	●	●	●	●	nd
E. coli	●	●	●	●	●	●	●	●	●	●	●	●	●	●	nd
Total coliform	●	●	●	●	●	●	●	●	●	●	●	●	●	●	nd
C. parvum	●	●	●	●	●	●	●	●	nd	nd	nd	nd	●	●	nd
Giardia lamblia	●	●	●	●	●	●	●	●	nd	nd	nd	nd	●	●	nd
Sewerage overflow events	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	●	●	●	●	nd

6.2 Spatial analysis of acute gastrointestinal illnesses

In this appendix, the study area for each case city (e.g., water utility service area) is described and mapped followed by a table of the AGI cases and incidence by FSA/ZIP code and maps of AGI incidence distribution by FSA/ZIP code.

To compare the geographic distribution of the health data with the cities' potable water distribution areas, water service area maps were obtained for each of the water treatment plants. These maps show that there are several municipalities that purchase wholesale potable water from the water utility in areas where health data were not obtained for this study.

Upon request, the Green Bay Water Utility and Hamilton Water provided GIS polygons of their service areas so identification of the respective ZIP codes and FSAs in their service areas should be accurate. Milwaukee Water Works and Toronto Water provided static maps of their services areas so identification of the respective ZIP codes and FSAs in their service areas was done by eye and do not accurately reflect their entire service areas. Receiving GIS polygons of all the water utility service areas would improve the accuracy of these maps.

Health data were obtained upon request from Public Health Ontario and the Wisconsin Department of Health Services, as described in the Phase 1 report (International Joint Commission Health Professionals Advisory Board 2017a).

Population data were obtained for Green Bay and Milwaukee, Wisconsin, from the 2010 US Census (US Census Bureau 2018) and ZIP code polygons obtained from ArcGIS Online – "Wisconsin Zip Codes" by WI_Legislature (2016-08-23).

Population data and FSA polygons were obtained for Hamilton and Toronto, Ontario, from the 2011 Census (Statistics Canada 2018).

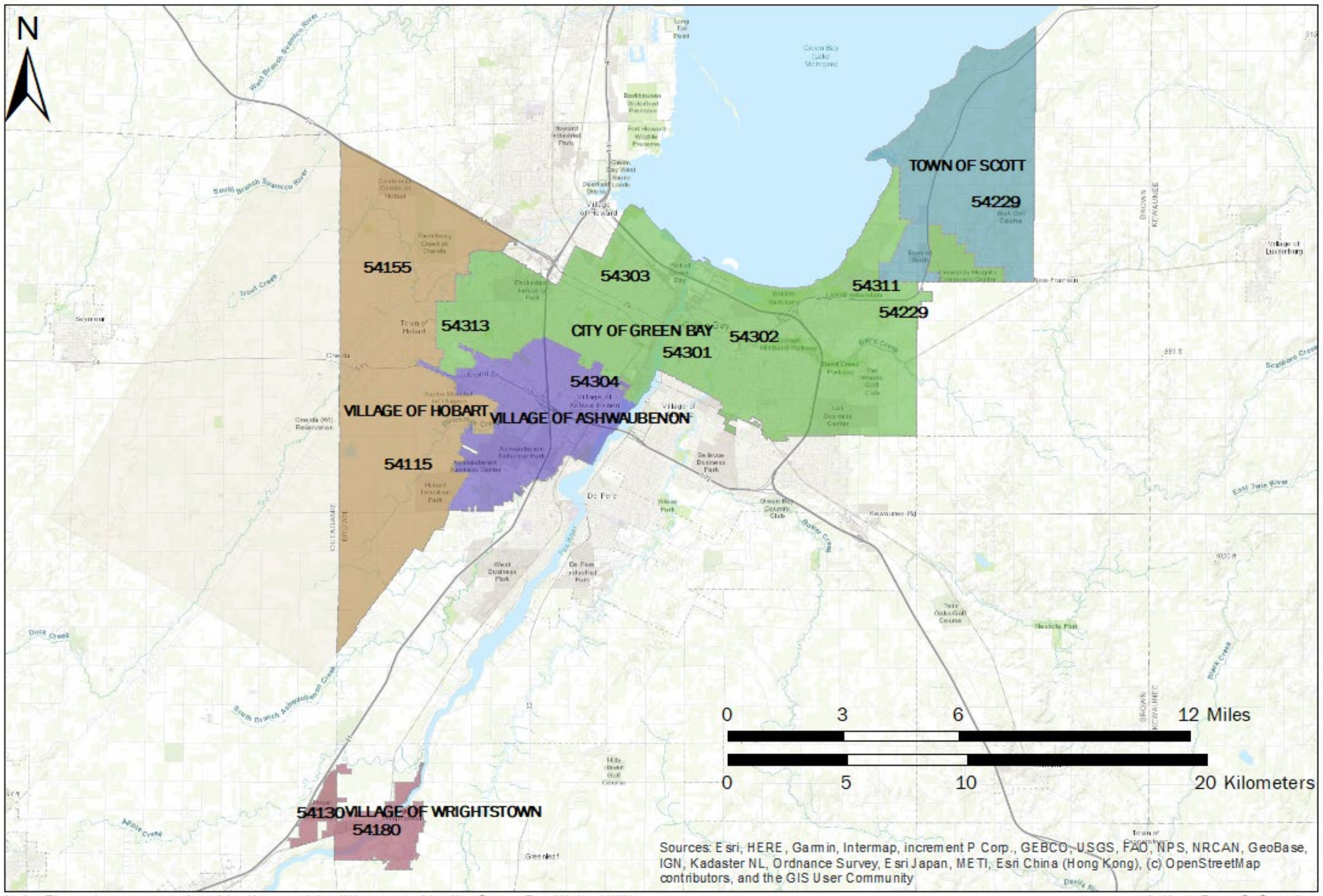
AGI cases were assigned to the specific ZIP code or FSA polygon center based on each patient's reported home address. ArcGIS software (ERSI, v.10.6.1, Redlands, CA, USA) was used to create the maps. Natural breaks (Jenks) were used to determine data classifications. The incidence (per 10,000 residents) was calculated according to the formula:

(cases / population) * 10,000.

Note the water utility service areas do not align with the FSA/ZIP code boundaries. Many FSAs/ZIP codes within the water utility service area extend beyond the utility service area where health data were included. Not all FSAs/ZIP codes within the water utility service areas were included due to health data limitations. Future studies should include health data from the entire water utility service area and not from areas beyond the service areas.

6.2.1 Green Bay Water Utility service area, acute gastrointestinal illnesses frequency table and spatial distribution

The Green Bay Water Utility provided GIS polygons of its service area (**Figure 6-1**) so identification of the 10 ZIP codes within its service area should be accurate. The cases and incidence of AGI and population by ZIP code are shown in **Table 6-3**. Maps of the spatial distribution by ZIP code of combined AGI incidence is shown in **Figure 6-2**, cryptosporidiosis incidence in **Figure 6-3**, and giardiasis incidence in **Figure 6-4**.



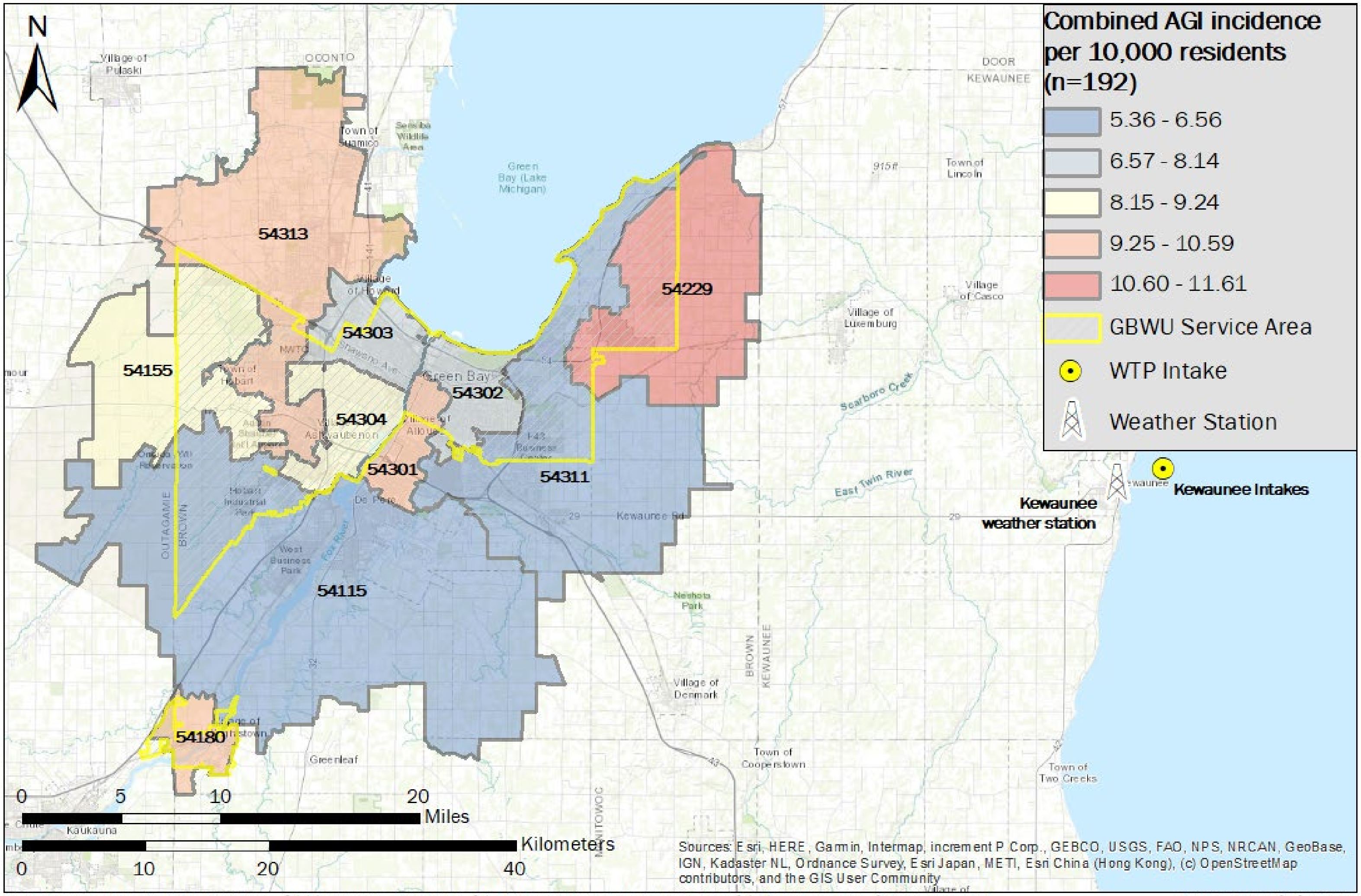
Note: The polygons are colored by the municipalities served by the Green Bay Water Utility.
The 11 ZIP codes within the service areas are labeled.
The boundaries of the ZIP codes are larger than the extent of the service areas.

Author: Ryan C. Graydon
Publication Date: 2020-01-22
Data source: Green Bay Water Utility

Figure 6-1: Green Bay Water Utility service area by municipality.

Table 6-3: Green Bay, Wisconsin AGI cases, incidence and population by ZIP code. These 10 ZIP codes are wholly or partially within the Green Bay Water Utility service area. Less than one percent of the geographic area of ZIP code 54130 is within the service area and therefore was not included. Health data are from January 1, 2009 through August 31, 2014. Incidence rate is per 10,000 residents.

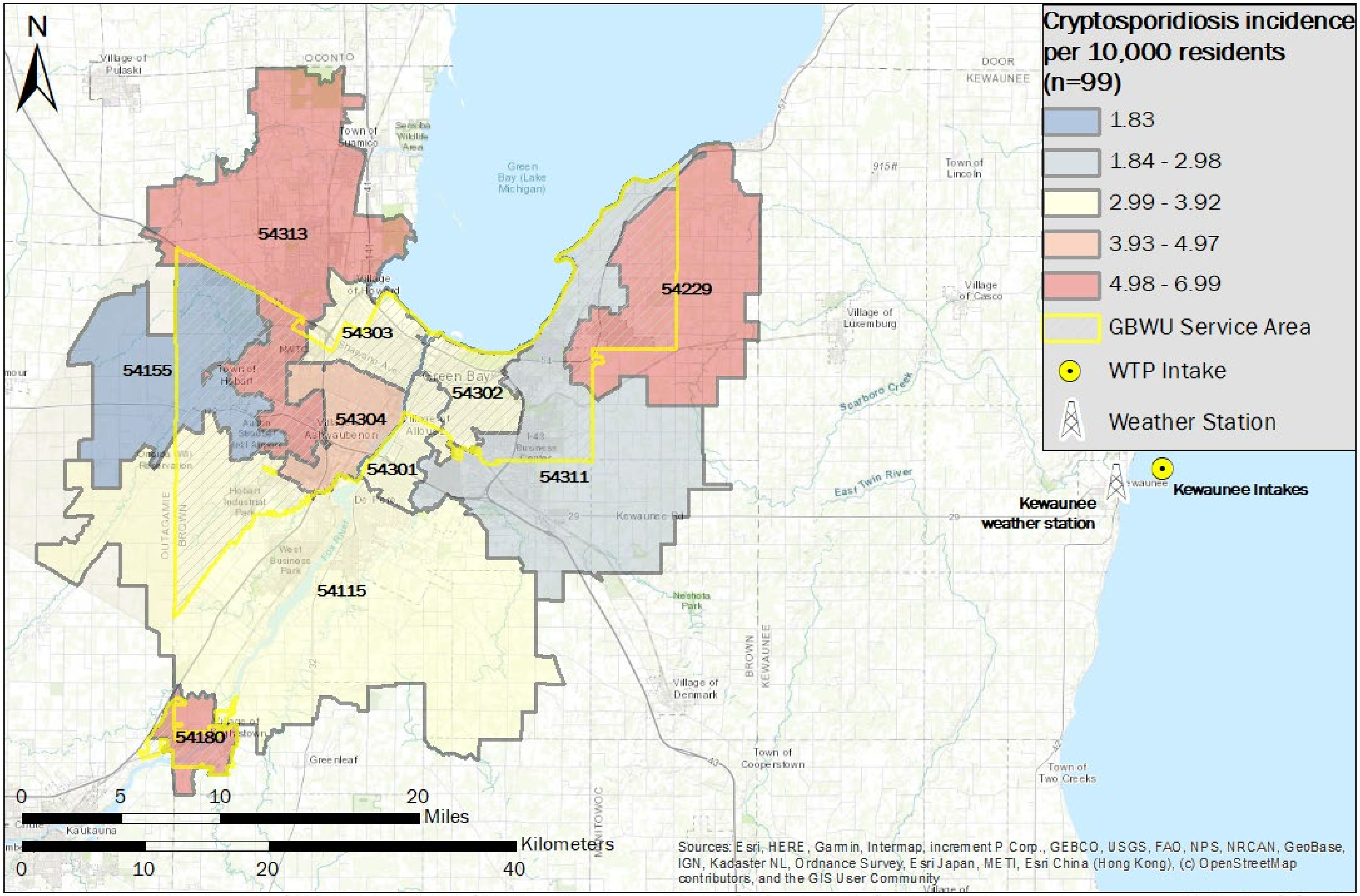
ZIP code	Cryptosporidiosis cases	Giardiasis cases	Combined AGI cases	Population (2010)	Population proportion	Cryptosporidiosis incidence	Giardiasis incidence	Combined AGI incidence
54115	16	11	27	41,178	17.8%	3.89	2.67	6.56
54155	1	4	5	5,451	2.4%	1.83	7.34	9.17
54180	2	1	3	2,861	1.2%	6.99	3.50	10.49
54229	3	2	5	4,306	1.9%	6.97	4.64	11.61
54301	8	16	24	22,742	9.8%	3.52	7.04	10.55
54302	12	12	24	30,611	13.2%	3.92	3.92	7.84
54303	10	12	22	27,041	11.7%	3.70	4.44	8.14
54304	14	12	26	28,153	12.1%	4.97	4.26	9.24
54311	10	8	18	33,580	14.5%	2.98	2.38	5.36
54313	23	15	38	35,897	15.5%	6.41	4.18	10.59
Totals	99	93	192	231,820	100%	4.27	4.01	8.28



Note: Health data are from January 1, 2009 through August 31, 2014. Population data are from the 2010 census (U.S. Census Bureau).
The Green Bay Water utility service area does not align with ZIP code boundaries.
Many ZIP codes within the utility service area extend beyond the service area where health data were also included.
Not all ZIP codes within the Green Bay Water utility service area were included due to limited health data.

Author: Ryan C. Graydon
Date: 2020-04-03

Figure 6-2: Green Bay, Wisconsin combined AGI incidence by ZIP code. There were 99 cases of cryptosporidiosis (4.27 cases per 10,000 residents) and 93 cases of giardiasis (4.01 cases per 10,000 residents) for a total of 192 laboratory-confirmed cases of AGI from January 1, 2009 through August 31, 2014. The incidence per 10,000 residents was calculated from 2010 census data for each of the 10 ZIP codes (N-231,820) (US Census Bureau 2018).



Note: Health data are from January 1, 2009 through August 31, 2014. Population data are from the 2010 census (U.S. Census Bureau).
The Green Bay Water utility service area does not align with ZIP code boundaries.
Many ZIP codes within the utility service area extend beyond the service area where health data were also included.
Not all ZIP codes within the Green Bay Water utility service area were included due to limited health data.

Author: Ryan C. Graydon
Date: 2020-04-03

Figure 6-3: Green Bay, Wisconsin cryptosporidiosis incidence by ZIP code. There were 99 cases of cryptosporidiosis (4.27 cases per 10,000 residents) from January 1, 2009 through August 31, 2014. The incidence per 10,000 residents was calculated from 2010 census data for each of the 10 ZIP codes (N=231,820) (US Census Bureau 2018).

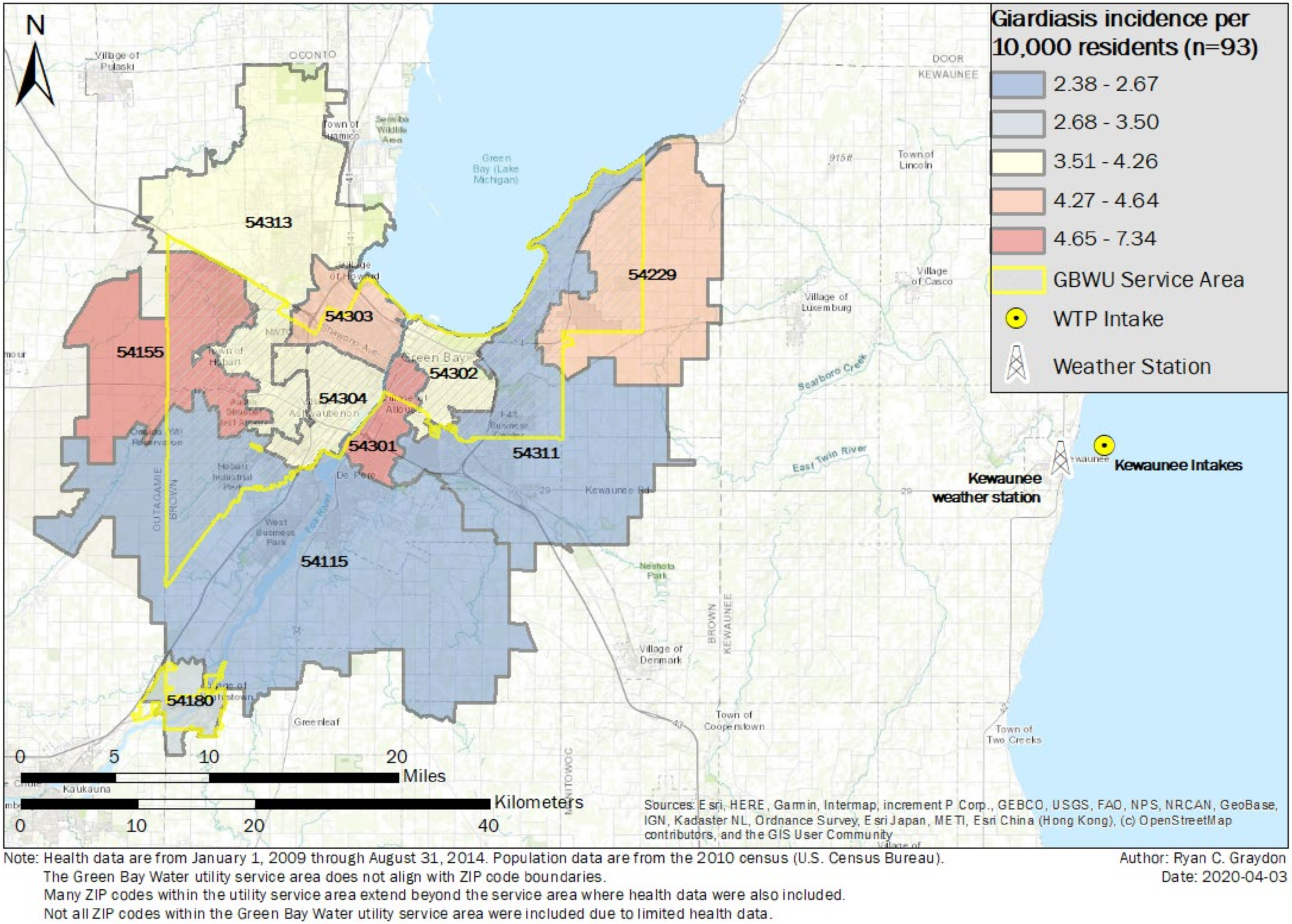
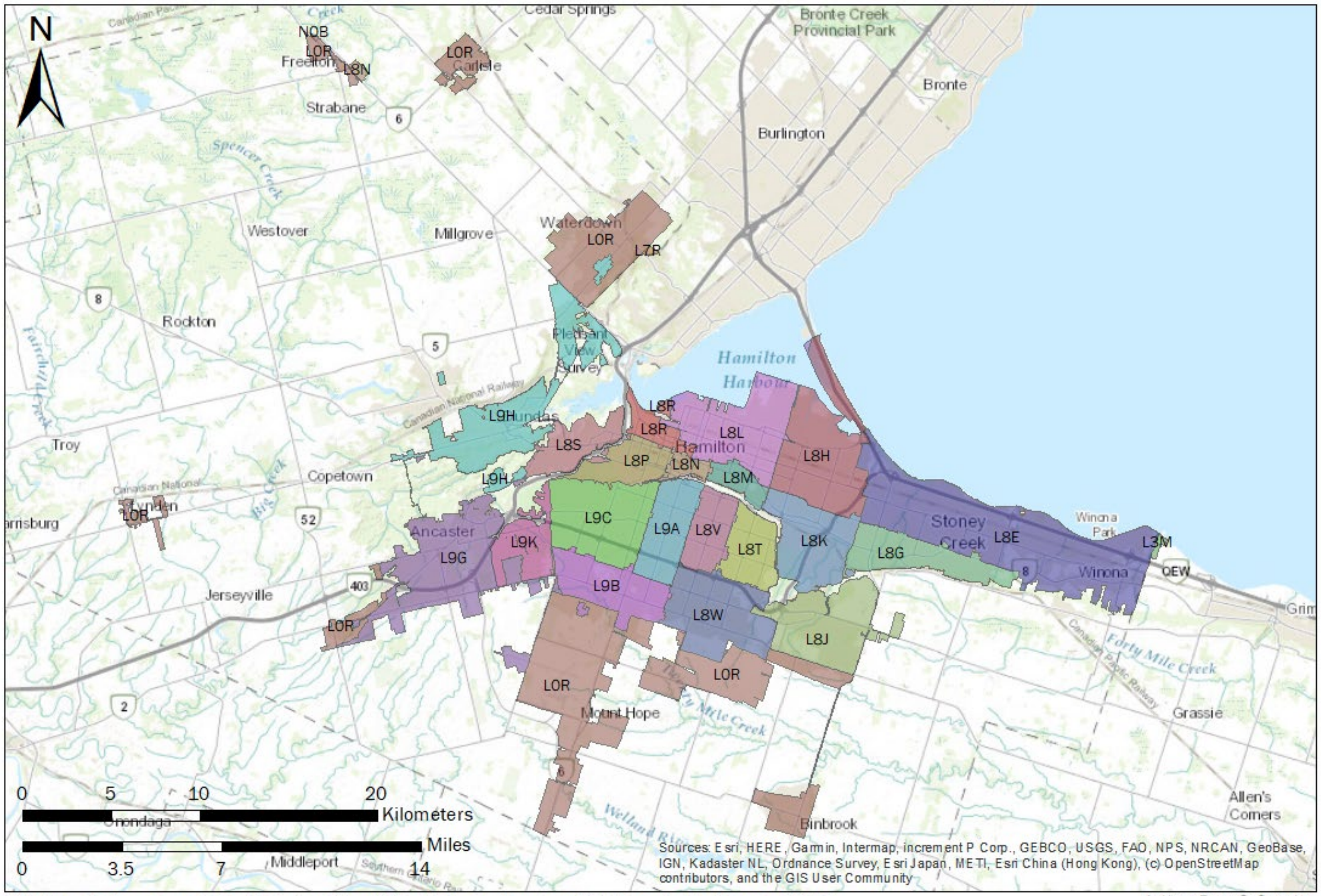


Figure 6-4: Green Bay, Wisconsin giardiasis incidence by ZIP code. There were 93 cases of giardiasis (4.01 cases per 10,000 residents) from January 1, 2009 through August 31, 2014. The incidence per 10,000 residents was calculated from 2010 census data for each of the 10 ZIP codes (N=231,820) (US Census Bureau 2018).

6.2.2 Hamilton Water service area, acute gastrointestinal illnesses frequency table and spatial distribution

Hamilton Water provided GIS polygons of its service area (**Figure 6-5**) so identification of the 24 FSAs within its service area should be accurate. The cases and incidence of AGI and population by FSA are shown in **Table 6-4**. Maps of the spatial distribution by FSA of combined AGI incidence is shown in **Figure 6-6**, cryptosporidiosis incidence in **Figure 6-7**, and giardiasis incidence in **Figure 6-8**.



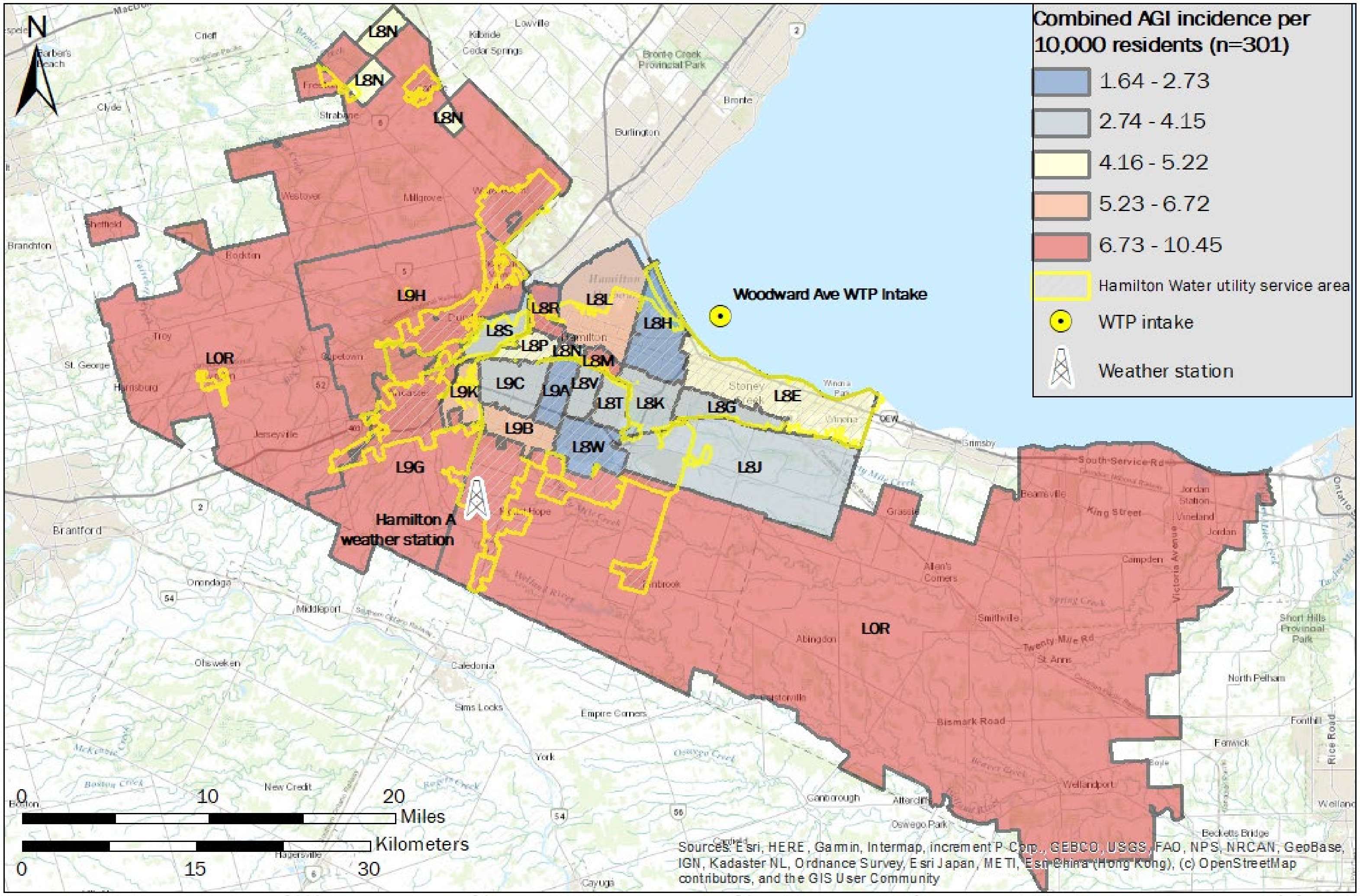
Note: The polygons are made from the intersection of the utility's service area and the forward sortation areas (FSAs).
The polygons are colored and labeled by the 24 FSAs within the service area.
The boundaries of the FSAs are larger than the extent of the service area.

Author: Ryan C. Graydon
Publication Date: 2020-01-17
Data sources: City of Hamilton - Public Works - Hamilton Water; Statistics Canada

Figure 6-5: Hamilton Water service area by Forward Sortation Area.

Table 6-4: Hamilton, Ontario AGI cases, incidence and population by FSA. These 21 FSAs are wholly or partially within the Hamilton Water utility service area. Less than once percent of the geographic areas of the FSAs L3M, L7R and N0B are within the service area and therefore were not included. Health data are from January 1, 2009 through August 31, 2014. Incidence rate is per 10,000 residents.

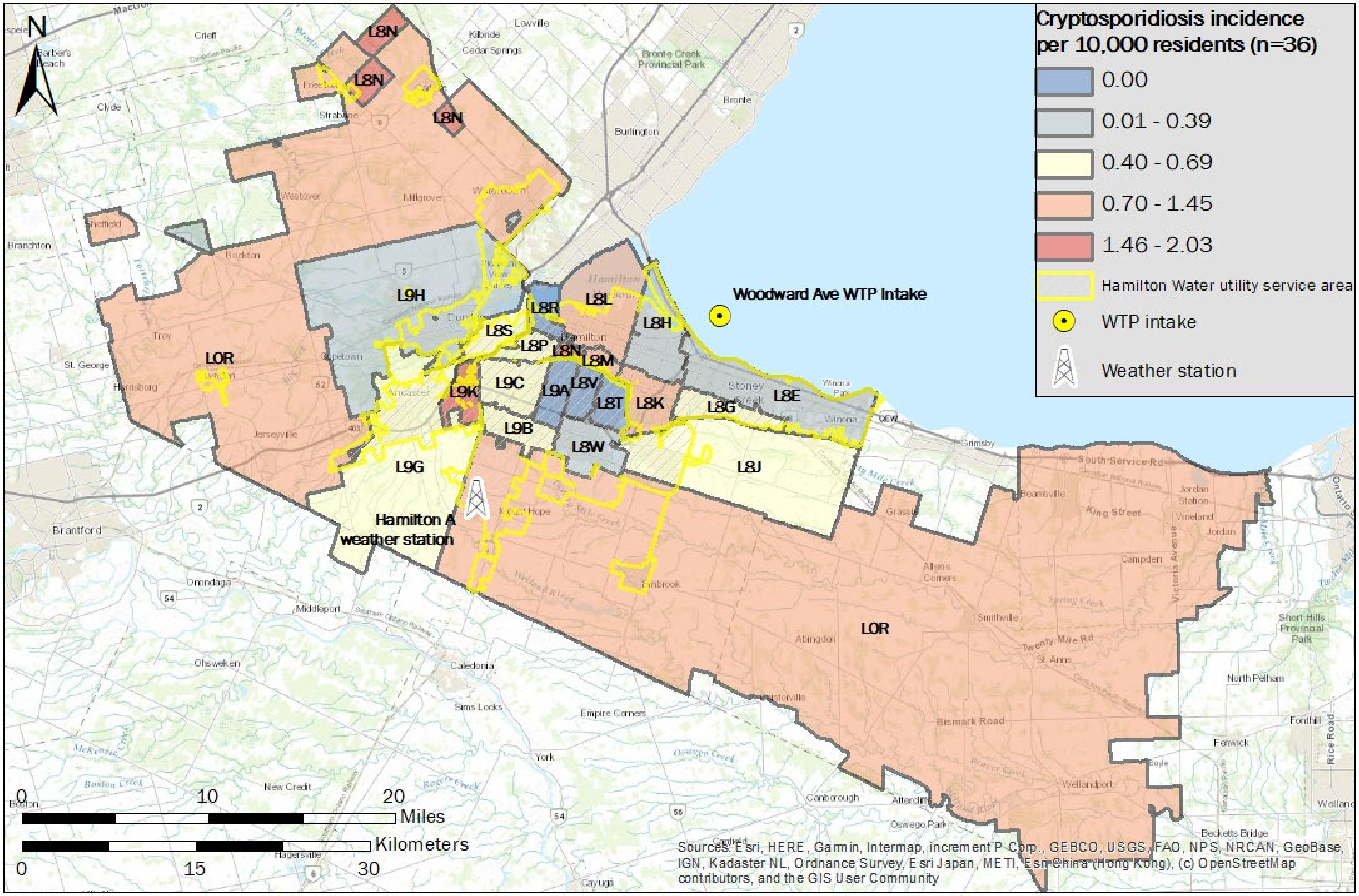
FSA	Cryptosporidiosis cases	Giardiasis cases	Combined AGI cases	Population (2011)	Population proportion	Cryptosporidiosis incidence	Giardiasis incidence	Combined AGI incidence
L0R	11	63	74	87,424	15.8%	1.26	7.21	8.46
L8E	1	19	20	38,320	6.9%	0.26	4.96	5.22
L8G	1	8	9	21,661	3.9%	0.46	3.69	4.15
L8H	1	4	5	26,285	4.8%	0.38	1.52	1.90
L8J	1	7	8	21,410	3.9%	0.47	3.27	3.74
L8K	3	10	13	31,832	5.8%	0.94	3.14	4.08
L8L	3	18	21	32,279	5.8%	0.93	5.58	6.51
L8M	2	9	11	13,835	2.5%	1.45	6.51	7.95
L8N	3	4	7	14,794	2.7%	2.03	2.70	4.73
L8P	1	10	11	21,950	4.0%	0.46	4.56	5.01
L8R	0	11	11	10,523	1.9%	0.00	10.45	10.45
L8S	1	4	5	14,494	2.6%	0.69	2.76	3.45
L8T	0	7	7	19,158	3.5%	0.00	3.65	3.65
L8V	0	7	7	21,325	3.9%	0.00	3.28	3.28
L8W	1	6	7	25,686	4.7%	0.39	2.34	2.73
L9A	0	4	4	24,409	4.4%	0.00	1.64	1.64
L9B	1	13	14	20,827	3.8%	0.48	6.24	6.72
L9C	2	12	14	39,951	7.2%	0.50	3.00	3.50
L9G	1	19	20	22,956	4.2%	0.44	8.28	8.71
L9H	1	25	26	31,593	5.7%	0.32	7.91	8.23
L9K	2	5	7	11,066	2.0%	1.81	4.52	6.33
Totals	36	265	301	551,778	100%	0.65	4.80	5.46



Note: Health data are from January 1, 2009 through August 31, 2014. Population data are from the 2011 census (Statistics Canada).
The Hamilton Water utility service area does not align with FSA boundaries.
Many FSAs within the utility service area extend beyond the service area where health data were also included.
Not all FSAs within the Hamilton Water utility service area were included due to limited health data.

Author: Ryan C. Graydon
Date: 2020-04-03

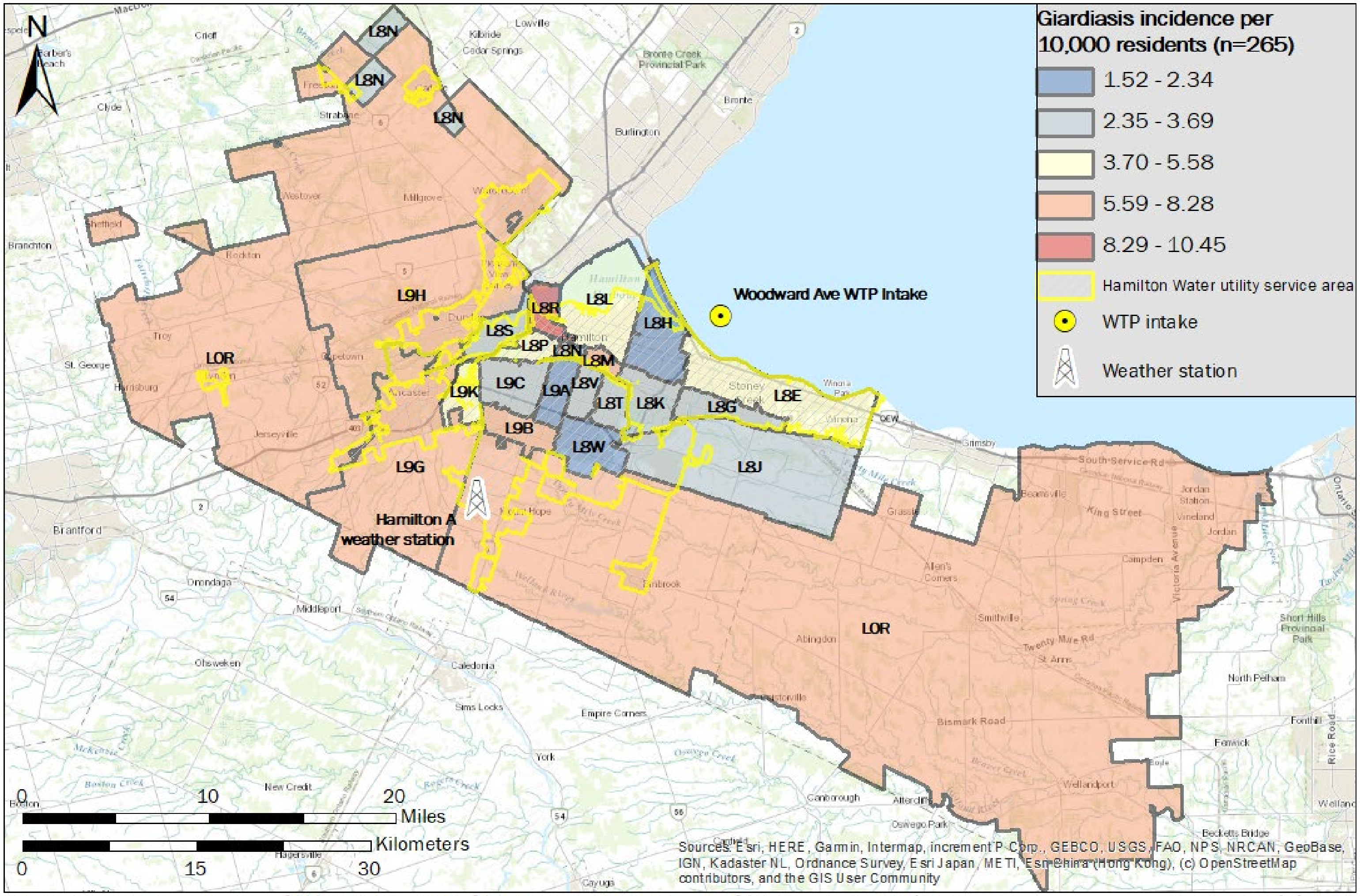
Figure 6-6: Hamilton, Ontario combined AGI incidence by FSA. There were 36 cases of cryptosporidiosis (0.65 cases per 10,000 residents) and 265 cases of giardiasis (4.80 cases per 10,000 residents) for a total of 301 laboratory-confirmed cases of AGI (5.46 cases per 10,000 residents) from January 1, 2009 through August 31, 2014. The incidence per 10,000 residents was calculated from 2011 census data for each of the 21 FSAs (N=551,778) (Statistics Canada 2018).



Note: Health data are from January 1, 2009 through August 31, 2014. Population data are from the 2011 census (Statistics Canada).
The Hamilton Water utility service area does not align with FSA boundaries.
Many FSAs within the utility service area extend beyond the service area where health data were also included.
Not all FSAs within the Hamilton Water utility service area were included due to limited health data.

Author: Ryan C. Graydon
Date: 2020-04-03

Figure 6-7: Hamilton, Ontario cryptosporidiosis incidence by FSA. There were 36 cases of cryptosporidiosis (0.65 cases per 10,000 residents) from January 1, 2009 through August 31, 2014. The incidence per 10,000 residents was calculated from 2011 census data for each of the 21 FSAs (N=551,778) (Statistics Canada 2018).



Note: Health data are from January 1, 2009 through August 31, 2014. Population data are from the 2011 census (Statistics Canada).
The Hamilton Water utility service area does not align with FSA boundaries.
Many FSAs within the utility service area extend beyond the service area where health data were also included.
Not all FSAs within the Hamilton Water utility service area were included due to limited health data.

Author: Ryan C. Graydon
Date: 2020-04-03

Figure 6-8: Hamilton, Ontario giardiasis incidence by FSA. There were 265 cases of giardiasis (4.80 cases per 10,000 residents) from January 1, 2009 through August 31, 2014. The incidence per 10,000 residents was calculated from 2011 census data for each of the 21 FSAs (N=551,778) (Statistics Canada 2018).

6.2.3 Milwaukee Water Works service area, acute gastrointestinal illnesses frequency table and spatial distribution

The Milwaukee Water Works provided a static map of its service area (**Figure 6-9**). To determine the study area, a map of the ZIP codes in the greater Milwaukee area was compared by eye to this static map from which 36 ZIP codes were identified to be within the utility service area. The identification of all the ZIP codes within the water service area could be improved with the GIS polygons of the service area. The cases and incidence of AGI and population by ZIP code are shown in **Table 6-5**. Maps of the spatial distribution by ZIP code of combined AGI incidence is shown in **Figure 6-10**, cryptosporidiosis incidence in **Figure 6-11**, and giardiasis incidence in **Figure 6-12**.

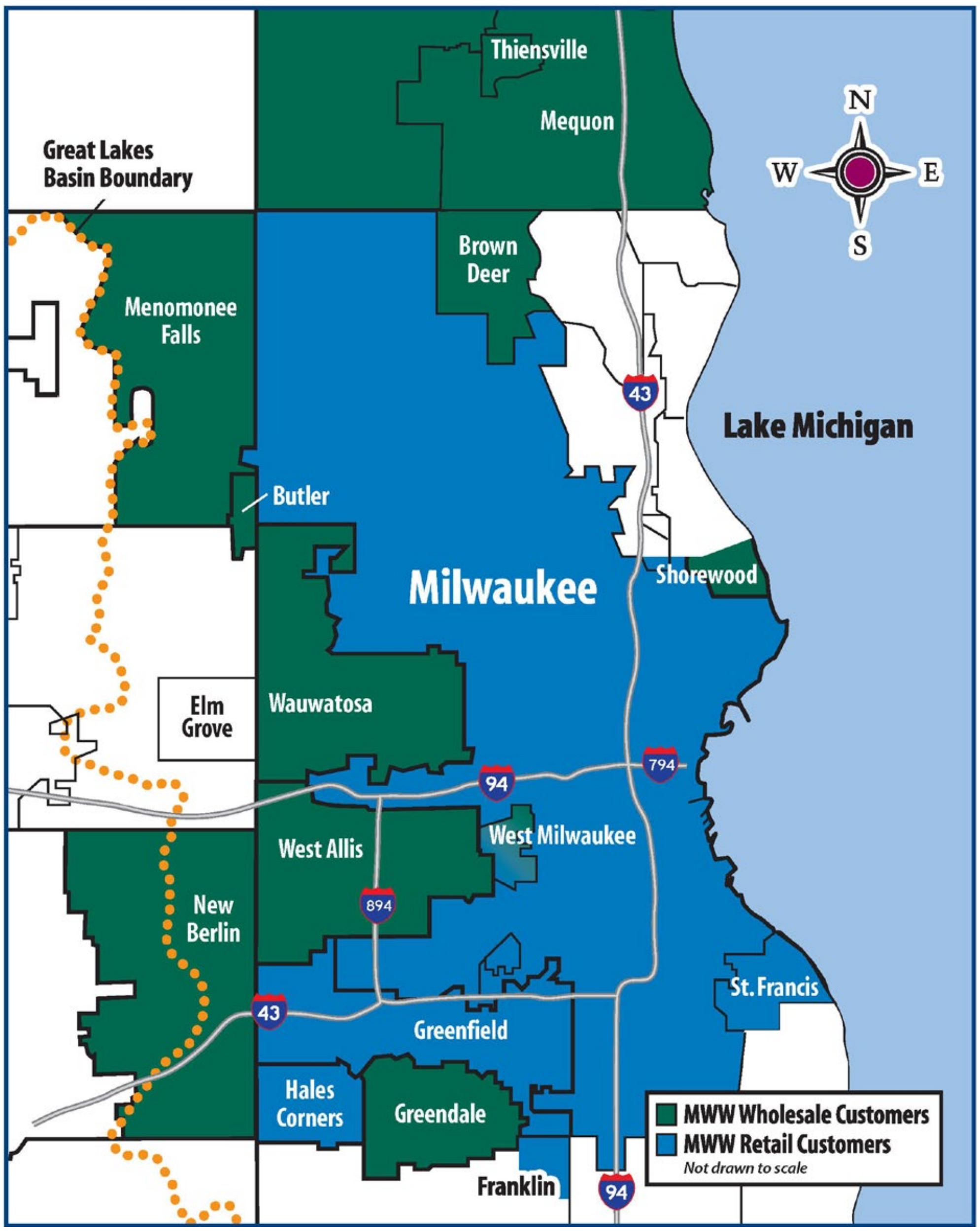
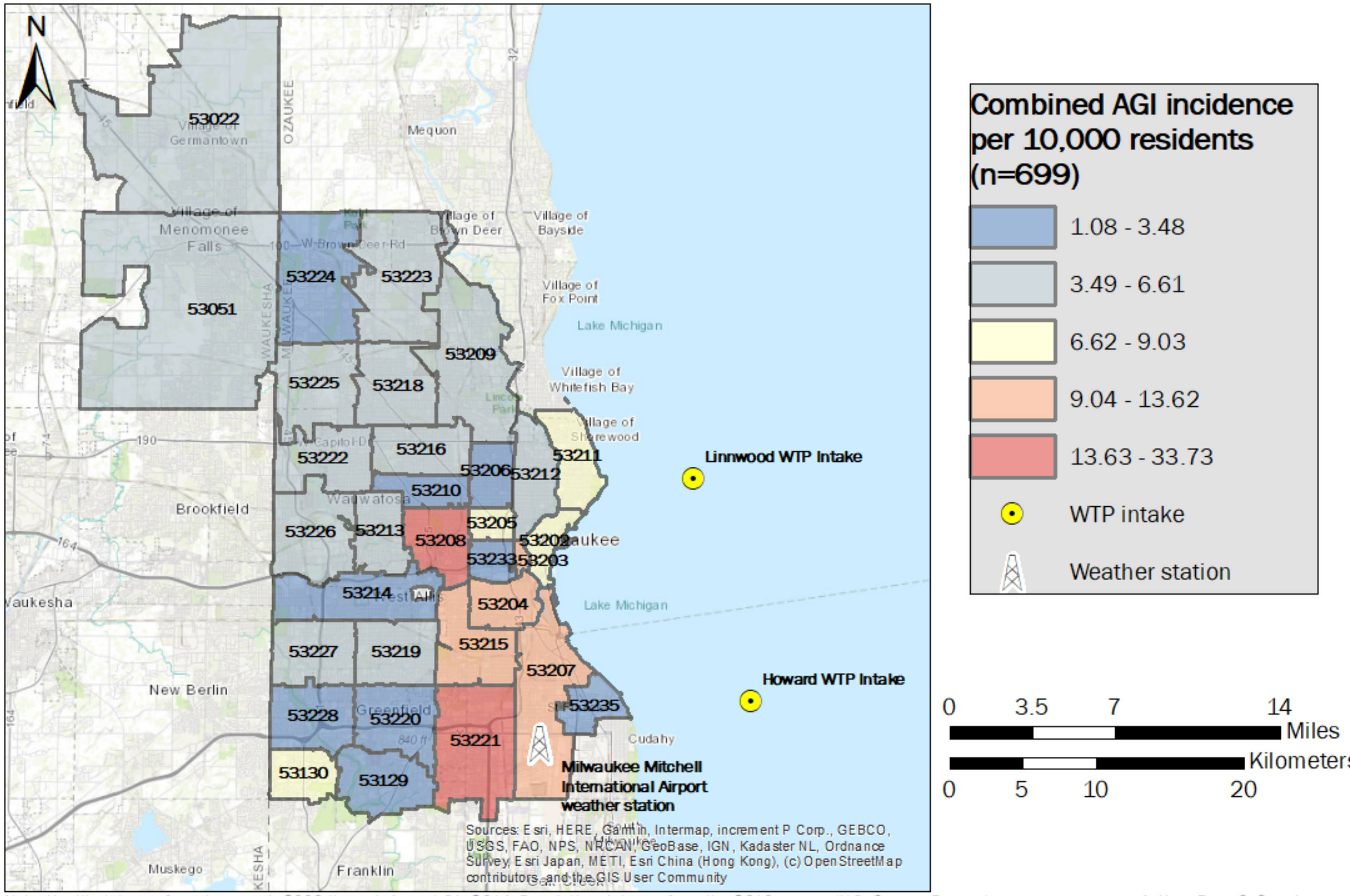


Figure 6-9: Milwaukee Water Works service area map. Image source: Milwaukee Water Works.

Table 6-5: Milwaukee, Wisconsin AGI cases, incidence and population by ZIP code. These 32 ZIP codes are wholly or partially within the Milwaukee Water Works utility service area. The ZIP codes 53007, 53092, 53097 and 53151 are also wholly or partially within the utility service area but were not included in our analyses because health data for these ZIP codes were not received. Health data are from January 1, 2009 through August 31, 2014. Incidence rate is per 10,000 residents.

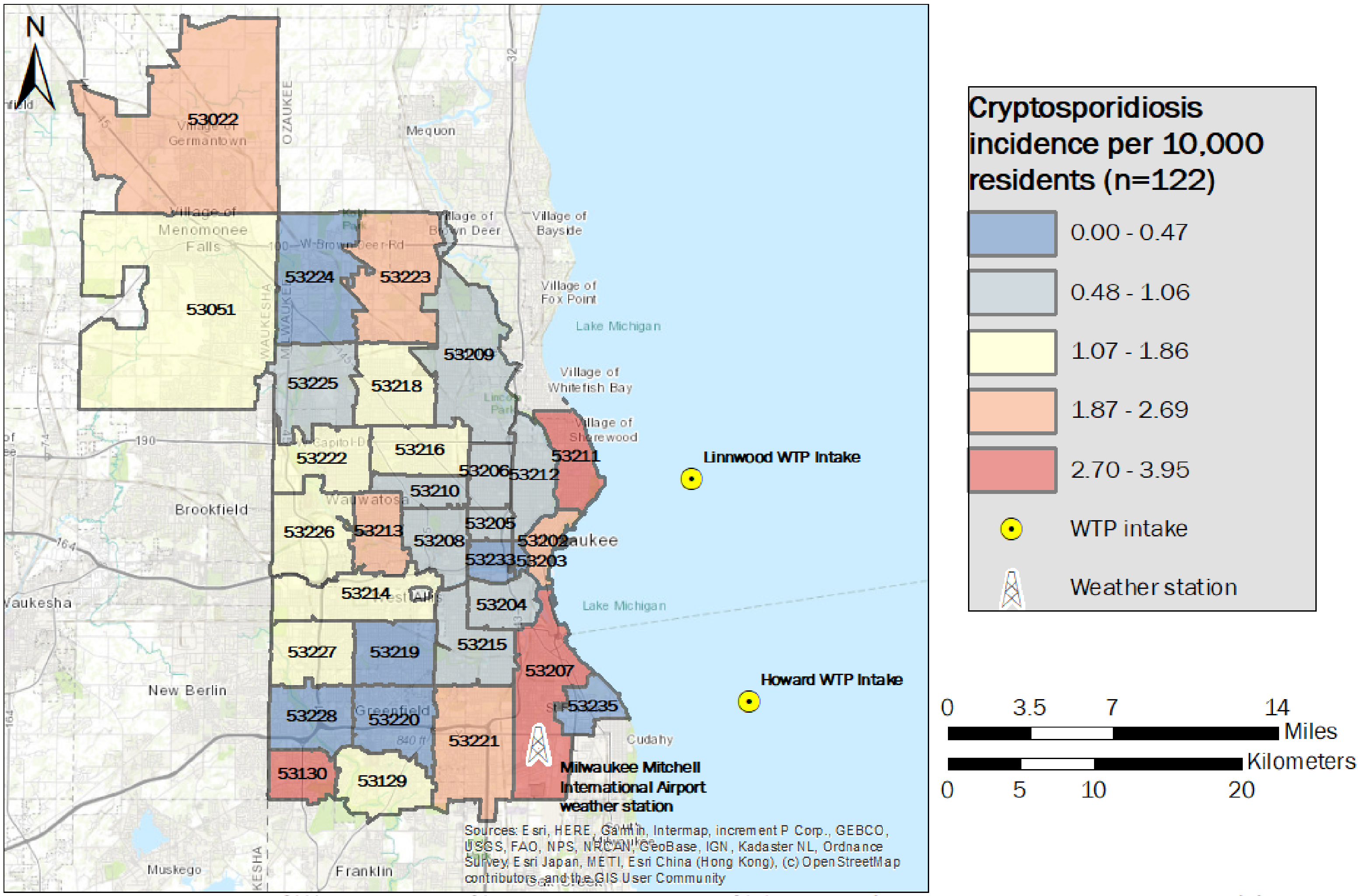
ZIP codes	Cryptosporidiosis cases	Giardiasis cases	Combined AGI cases	Population (2010)	Population proportion	Cryptosporidiosis incidence	Giardiasis incidence	Combined AGI incidence
53022	5	6	11	18,920	2.2%	2.64	3.17	5.81
53051	5	11	16	35,651	4.1%	1.40	3.09	4.49
53129	2	2	4	13,973	1.6%	1.43	1.43	2.86
53130	3	4	7	7,755	0.9%	3.87	5.16	9.03
53202	6	15	21	23,386	2.7%	2.57	6.41	8.98
53203	0	1	1	938	0.1%	0.00	10.66	10.66
53204	3	52	55	42,355	4.9%	0.71	12.28	12.99
53205	1	7	8	10,050	1.2%	1.00	6.97	7.96
53206	3	3	6	28,210	3.3%	1.06	1.06	2.13
53207	11	29	40	35,149	4.1%	3.13	8.25	11.38
53208	3	102	105	31,133	3.6%	0.96	32.76	33.73
53209	4	16	20	46,917	5.4%	0.85	3.41	4.26
53210	2	5	7	28,126	3.3%	0.71	1.78	2.49
53211	14	16	30	35,406	4.1%	3.95	4.52	8.47
53212	2	18	20	30,416	3.5%	0.66	5.92	6.58
53213	7	9	16	26,020	3.0%	2.69	3.46	6.15
53214	5	5	10	34,725	4.0%	1.44	1.44	2.88
53215	5	78	83	60,953	7.1%	0.82	12.80	13.62
53216	6	11	17	32,264	3.7%	1.86	3.41	5.27
53218	6	18	24	40,625	4.7%	1.48	4.43	5.91
53219	1	18	19	33,880	3.9%	0.30	5.31	5.61
53220	1	5	6	26,303	3.0%	0.38	1.90	2.28
53221	8	81	89	37,701	4.4%	2.12	21.48	23.61
53222	4	11	15	25,165	2.9%	1.59	4.37	5.96
53223	6	8	14	29,230	3.4%	2.05	2.74	4.79
53224	1	4	5	21,284	2.5%	0.47	1.88	2.35
53225	2	15	17	25,706	3.0%	0.78	5.84	6.61
53226	3	8	11	18,370	2.1%	1.63	4.35	5.99
53227	3	9	12	23,357	2.7%	1.28	3.85	5.14
53228	0	5	5	14,369	1.7%	0.00	3.48	3.48
53233	0	4	4	16,453	1.9%	0.00	2.43	2.43
53235	0	1	1	9,270	1.1%	0.00	1.08	1.08
Totals	122	577	699	864,060	100%	1.41	6.68	8.09



Note: Health data are from January 1, 2009 through August 31, 2014. Population data are from the 2010 census (U.S. Census Bureau).
The Milwaukee Water Works utility service area does not align with ZIP code boundaries.
Many ZIP codes within the utility service area extend beyond the service area where health data were also included.
Not all ZIP codes within the utility service area were included due to limited health data.

Author: Ryan C. Graydon
Date: 2020-04-03

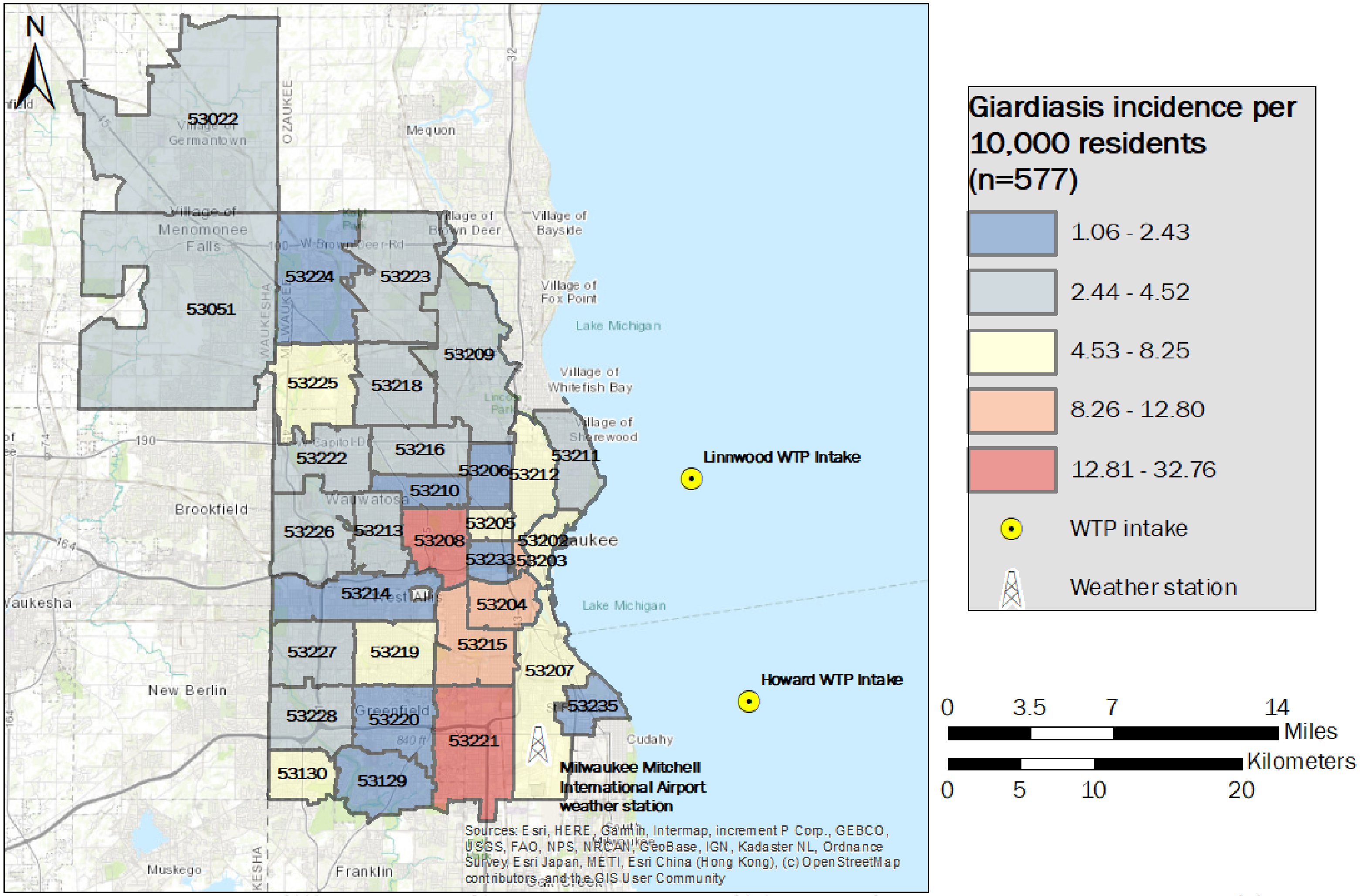
Figure 6-10: Milwaukee, Wisconsin combined AGI incidence by ZIP code. There were 122 cases of cryptosporidiosis (1.41 cases per 10,000 residents) and 577 cases of giardiasis (6.68 cases per 10,000 residents) for a total of 699 laboratory-confirmed cases of AGI (8.09 cases per 10,000 residents) from January 1, 2009 through August 31, 2014. The incidence per 10,000 residents was calculated from 2010 census data for each of the 32 ZIP codes (N=864,060) (US Census Bureau 2018).



Note: Health data are from January 1, 2009 through August 31, 2014. Population data are from the 2010 census (U.S. Census Bureau).
The Milwaukee Water Works utility service area does not align with ZIP code boundaries.
Many ZIP codes within the utility service area extend beyond the service area where health data were also included.
Not all ZIP codes within the utility service area were included due to limited health data.

Author: Ryan C. Graydon
Date: 2020-04-03

Figure 6- 11: Milwaukee, Wisconsin cryptosporidiosis incidence by ZIP code. There were 122 cases of cryptosporidiosis (1.41 cases per 10,000 residents) from January 1, 2009 through August 31, 2014. The incidence per 10,000 residents was calculated from 2010 census data for each of the 32 ZIP codes (N=864,020) (US Census Bureau 2018).



Note: Health data are from January 1, 2009 through August 31, 2014. Population data are from the 2010 census (U.S. Census Bureau).
The Milwaukee Water Works utility service area does not align with ZIP code boundaries.
Many ZIP codes within the utility service area extend beyond the service area where health data were also included.
Not all ZIP codes within the utility service area were included due to limited health data.

Author: Ryan C. Graydon
Date: 2020-04-03

Figure 6-12: Milwaukee, Wisconsin giardiasis incidence by ZIP code. There were 577 cases of giardiasis (6.68 cases per 10,000 residents) from January 1, 2009 through August 31, 2014. The incidence per 10,000 residents was calculated from 2010 census data for each of the 32 ZIP codes (N=864,020) (US Census Bureau 2018).

6.2.4 Toronto Water service area, acute gastrointestinal illnesses frequency table and spatial distribution

Toronto Water provided static maps of the water pressure zone districts for each of its four water treatment plants: Clark (**Figure 6-13**), Harris (**Figure 6-14**), Horgan (**Figure 6-15**) and Island (**Figure 6-16**). To determine the study area, the 96 FSAs that comprise the City of Toronto were included in our study. There are numerous areas beyond the city that also receive water service from Toronto Water but were not included. The identification of all the FSAs within its service area could be done with the GIS polygons of its service area. The cases and incidence of AGI and population by FSA are shown in **Table 6-6**. Maps of the spatial distribution by FSA of combined AGI incidence is shown in **Figure 6-17**, cryptosporidiosis incidence in **Figure 6-18**, and giardiasis incidence in **Figure 6-19**.

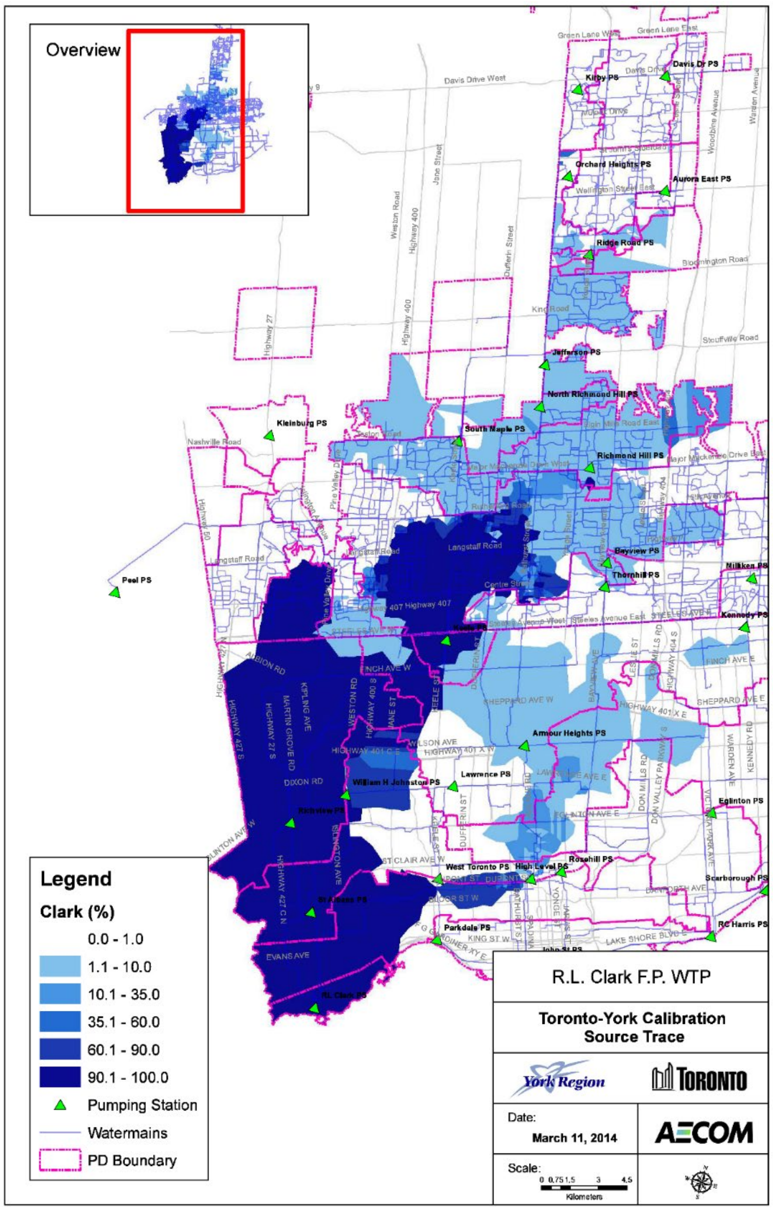


Figure 6-13: Toronto, Ontario Clark water treatment plant pressurized district boundaries. Image source: Toronto Water.

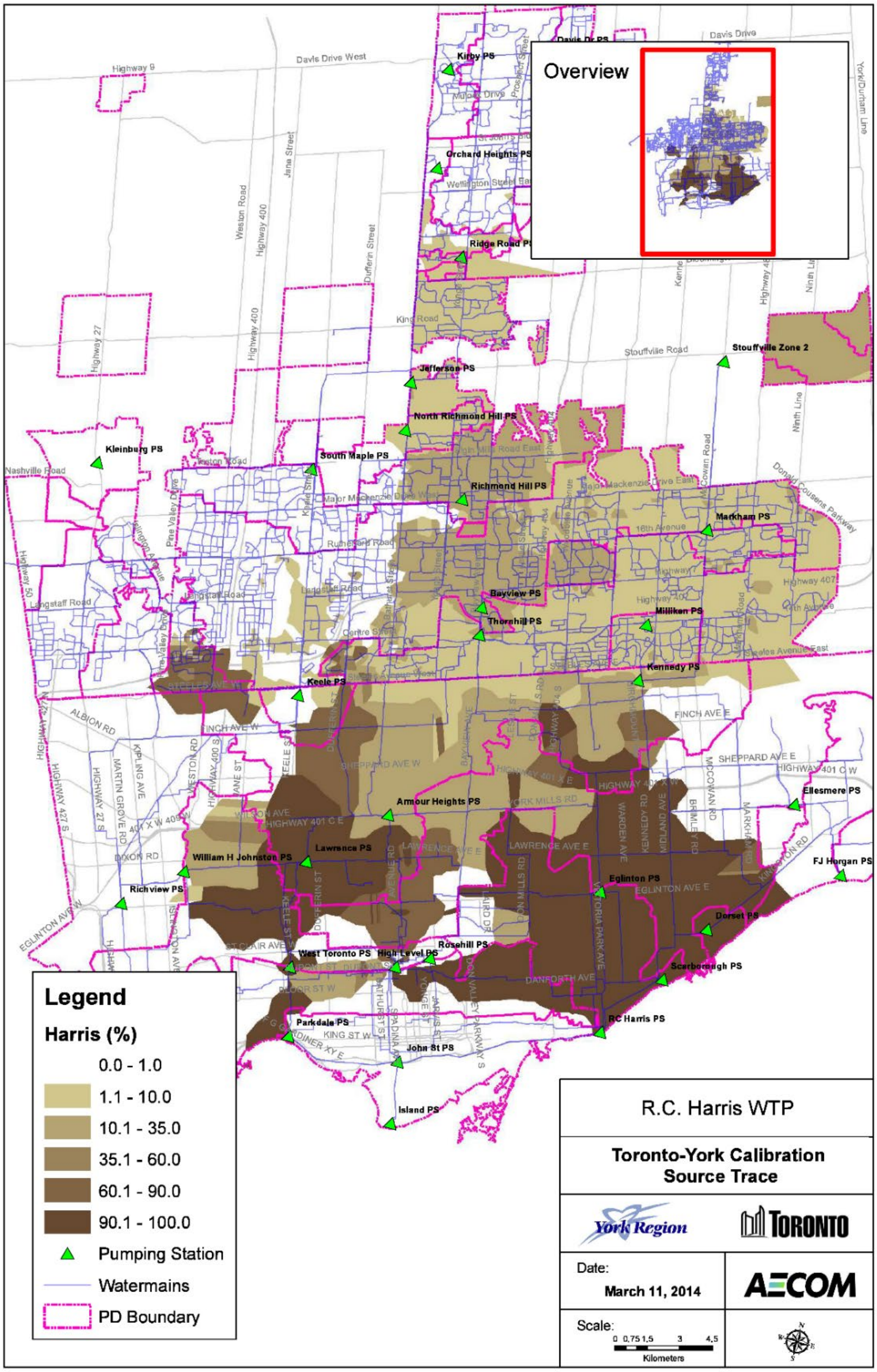


Figure 6-14: Toronto, Ontario Harris water treatment plant pressurized district boundaries. Image credit: Toronto Water.

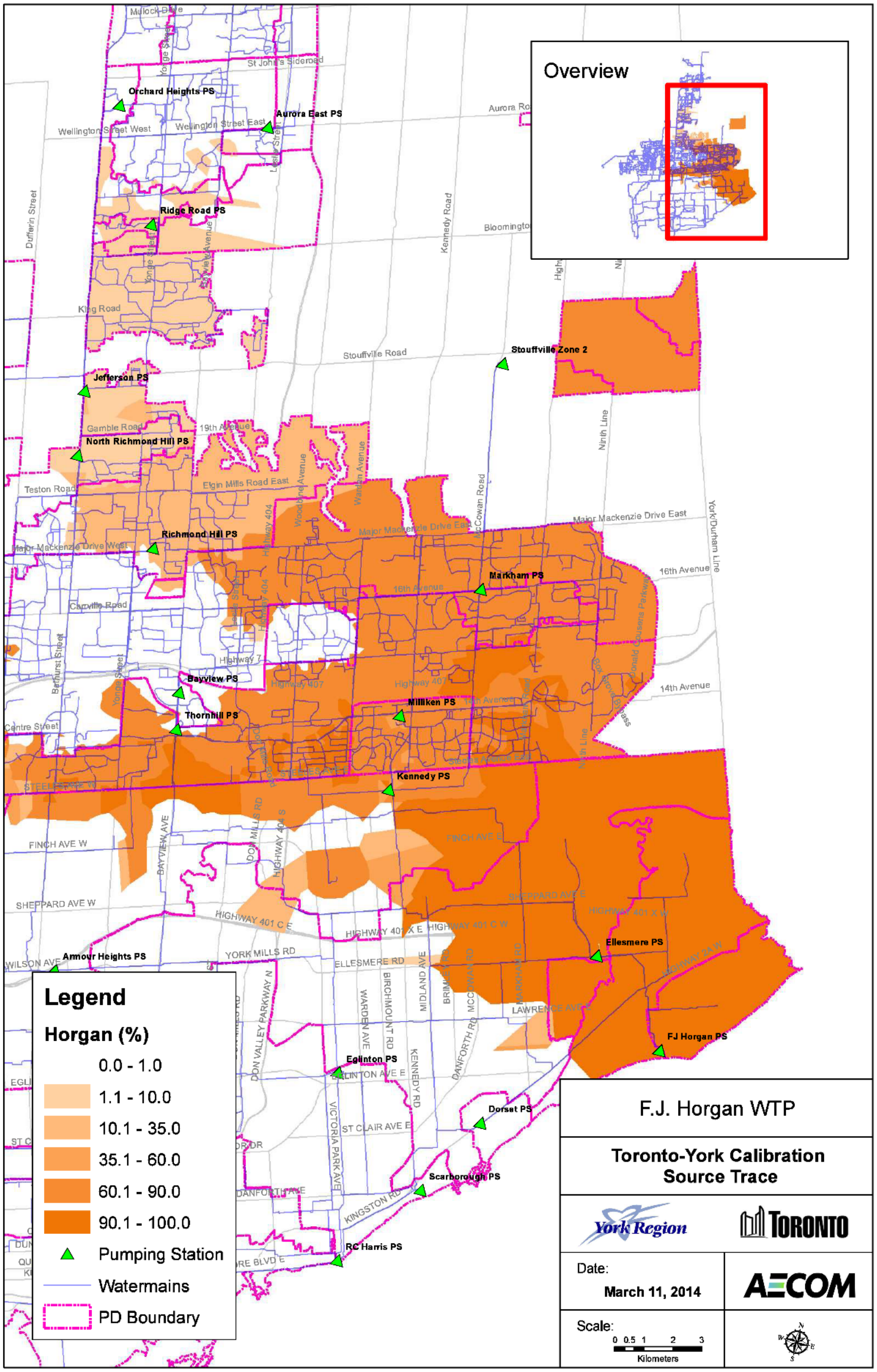


Figure 6-15: Toronto, Ontario Horgan water treatment plant pressurized district boundaries. Image credit: Toronto Water.

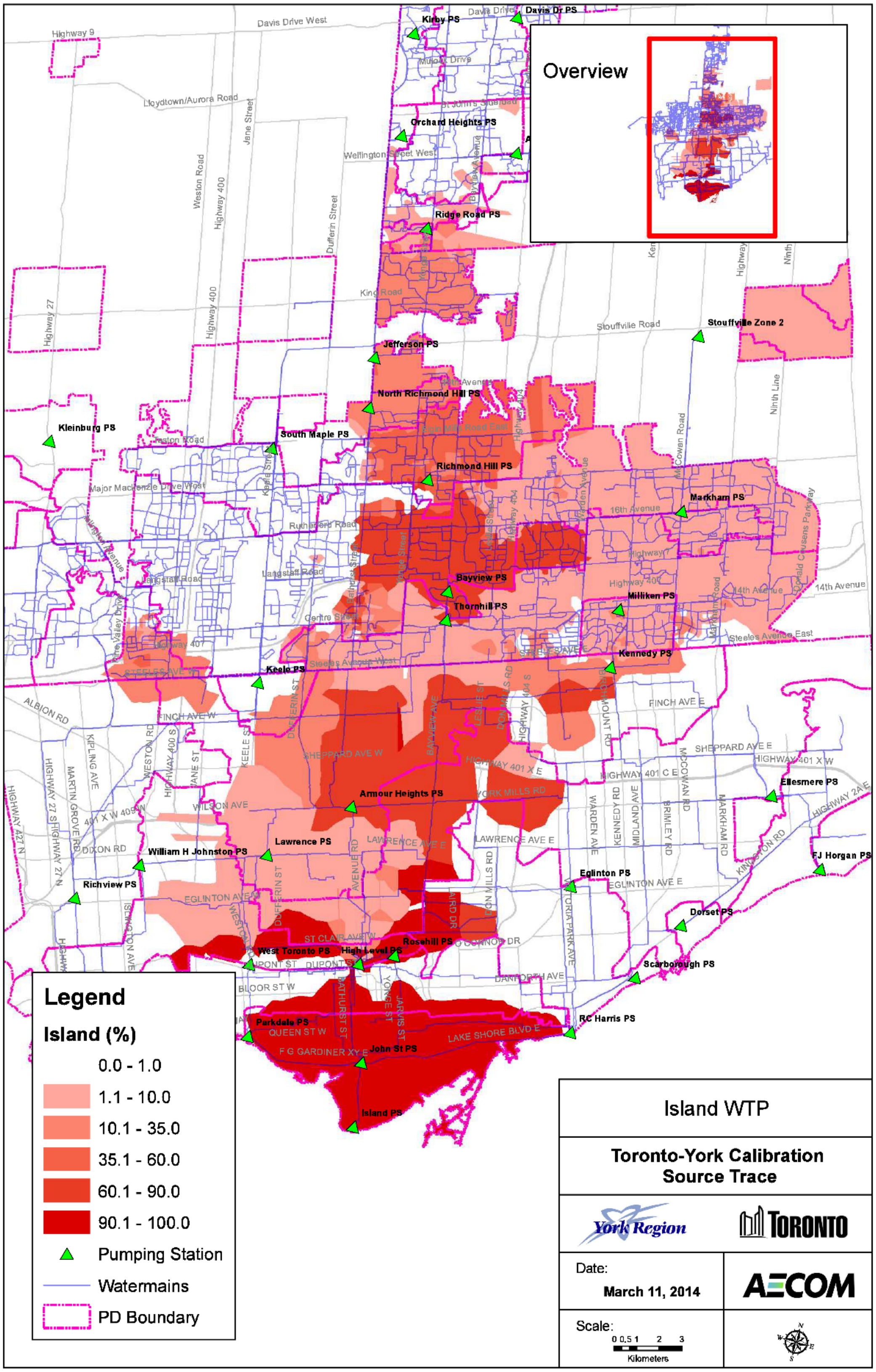
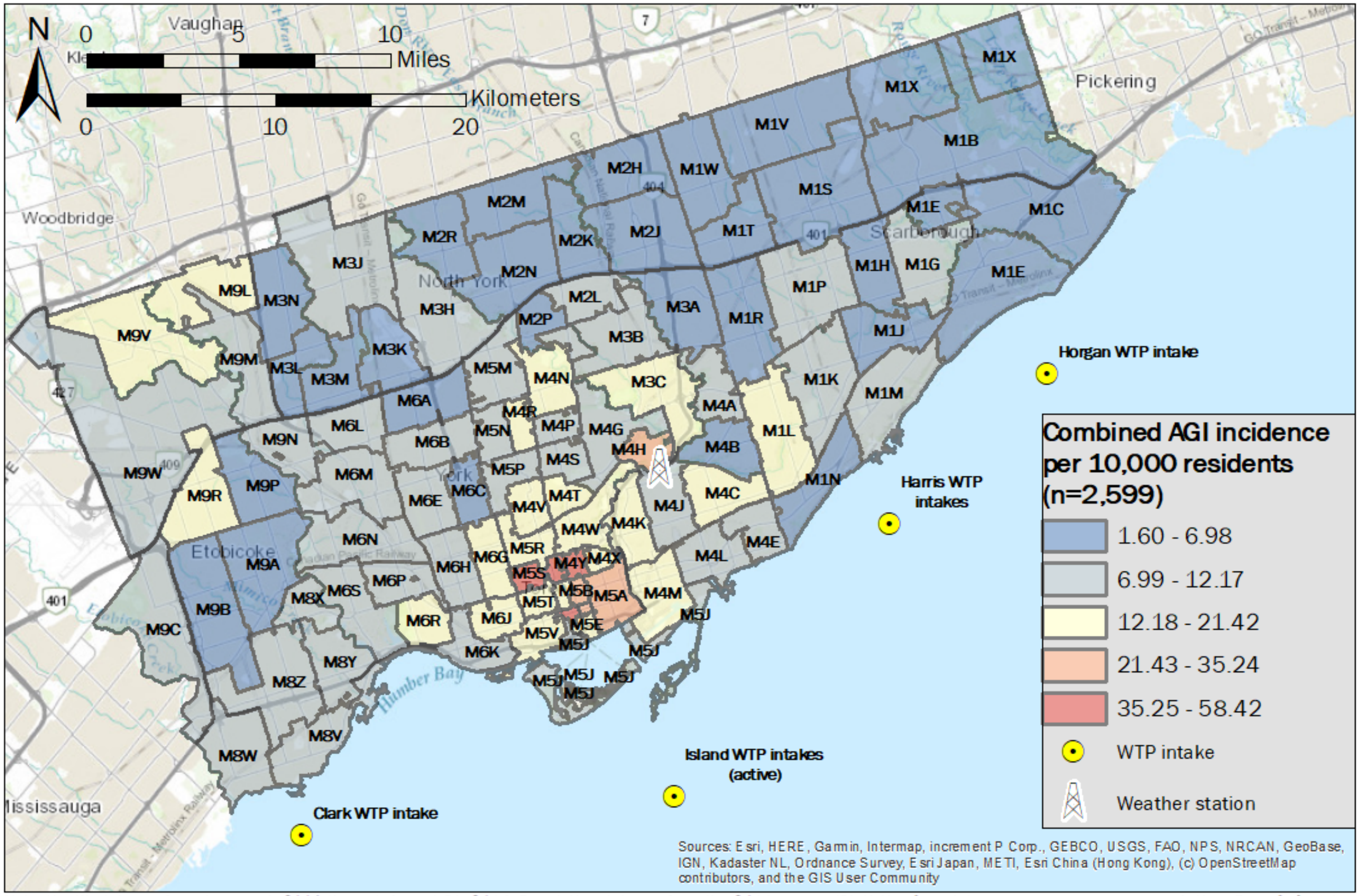


Figure 6-16: Toronto, Ontario Island water treatment plant pressurized district boundaries. Image credit: Toronto Water.

Table 6-6: Toronto, Ontario AGI cases, incidence and population by FSA. These 96 FSAs are wholly or partially within the Toronto Water utility service area. Additional FSAs are within the water utility service area and could be identified with the service area's GIS polygons. Health data are from January 1, 2009 through August 31, 2014. Incidence rate is per 10,000 residents.

FSA	Cryptosporidiosis cases	Giardiasis cases	Combined AGI cases	Population (2011)	Population proportion	Cryptosporidiosis incidence	Giardiasis incidence	Combined AGI incidence
M1B	4	20	24	67,251	2.6%	0.59	2.97	3.57
M1C	3	9	12	35,601	1.4%	0.84	2.53	3.37
M1E	1	21	22	46,398	1.8%	0.22	4.53	4.74
M1G	3	21	24	30,243	1.2%	0.99	6.94	7.94
M1H	2	12	14	23,706	0.9%	0.84	5.06	5.91
M1J	1	18	19	36,163	1.4%	0.28	4.98	5.25
M1K	6	32	38	47,286	1.8%	1.27	6.77	8.04
M1L	7	37	44	32,981	1.3%	2.12	11.22	13.34
M1M	3	14	17	22,919	0.9%	1.31	6.11	7.42
M1N	1	14	15	21,505	0.8%	0.47	6.51	6.98
M1P	7	39	46	43,305	1.7%	1.62	9.01	10.62
M1R	1	14	15	28,943	1.1%	0.35	4.84	5.18
M1S	1	8	9	36,505	1.4%	0.27	2.19	2.47
M1T	0	7	7	34,364	1.3%	0.00	2.04	2.04
M1V	4	5	9	56,313	2.2%	0.71	0.89	1.60
M1W	4	13	17	49,590	1.9%	0.81	2.62	3.43
M1X	2	4	6	14,744	0.6%	1.36	2.71	4.07
M2H	1	12	13	25,331	1.0%	0.39	4.74	5.13
M2J	3	30	33	54,104	2.1%	0.55	5.54	6.10
M2K	2	9	11	19,897	0.8%	1.01	4.52	5.53
M2L	1	8	9	12,025	0.5%	0.83	6.65	7.48
M2M	3	10	13	32,696	1.3%	0.92	3.06	3.98
M2N	4	23	27	67,114	2.6%	0.60	3.43	4.02
M2P	0	3	3	7,813	0.3%	0.00	3.84	3.84
M2R	3	18	21	39,583	1.5%	0.76	4.55	5.31
M3A	1	16	17	34,435	1.3%	0.29	4.65	4.94
M3B	0	11	11	13,499	0.5%	0.00	8.15	8.15
M3C	9	54	63	38,289	1.5%	2.35	14.10	16.45
M3H	2	27	29	34,535	1.3%	0.58	7.82	8.40
M3J	4	19	23	25,356	1.0%	1.58	7.49	9.07
M3K	0	2	2	5,889	0.2%	0.00	3.40	3.40
M3L	1	8	9	18,000	0.7%	0.56	4.44	5.00
M3M	0	13	13	23,727	0.9%	0.00	5.48	5.48
M3N	0	27	27	42,762	1.6%	0.00	6.31	6.31
M4A	2	12	14	14,150	0.5%	1.41	8.48	9.89
M4B	0	12	12	18,453	0.7%	0.00	6.50	6.50
M4C	8	52	60	45,822	1.8%	1.75	11.35	13.09
M4E	4	20	24	24,598	0.9%	1.63	8.13	9.76
M4G	2	17	19	18,030	0.7%	1.11	9.43	10.54
M4H	1	61	62	18,478	0.7%	0.54	33.01	33.55
M4J	6	35	41	35,146	1.3%	1.71	9.96	11.67
M4K	4	48	52	31,624	1.2%	1.26	15.18	16.44
M4L	2	28	30	31,544	1.2%	0.63	8.88	9.51
M4M	5	38	43	23,135	0.9%	2.16	16.43	18.59
M4N	1	22	23	15,194	0.6%	0.66	14.48	15.14
M4P	4	14	18	19,185	0.7%	2.08	7.30	9.38
M4R	1	15	16	11,048	0.4%	0.91	13.58	14.48
M4S	3	22	25	25,627	1.0%	1.17	8.58	9.76
M4T	1	20	21	10,094	0.4%	0.99	19.81	20.80
M4V	6	31	37	17,271	0.7%	3.47	17.95	21.42
M4W	7	21	28	14,022	0.5%	4.99	14.98	19.97
M4X	2	34	36	20,387	0.8%	0.98	16.68	17.66
M4Y	10	105	115	26,207	1.0%	3.82	40.07	43.88
M5A	9	75	84	34,649	1.3%	2.60	21.65	24.24
M5B	2	38	40	11,352	0.4%	1.76	33.47	35.24
M5C	0	9	9	2,974	0.1%	0.00	30.26	30.26
M5E	1	9	10	6,436	0.2%	1.55	13.98	15.54
M5G	2	10	12	7,001	0.3%	2.86	14.28	17.14
M5H	0	6	6	1,027	0.0%	0.00	58.42	58.42
M5J	2	8	10	10,454	0.4%	1.91	7.65	9.57
M5M	2	26	28	25,852	1.0%	0.77	10.06	10.83
M5N	0	13	13	16,349	0.6%	0.00	7.95	7.95

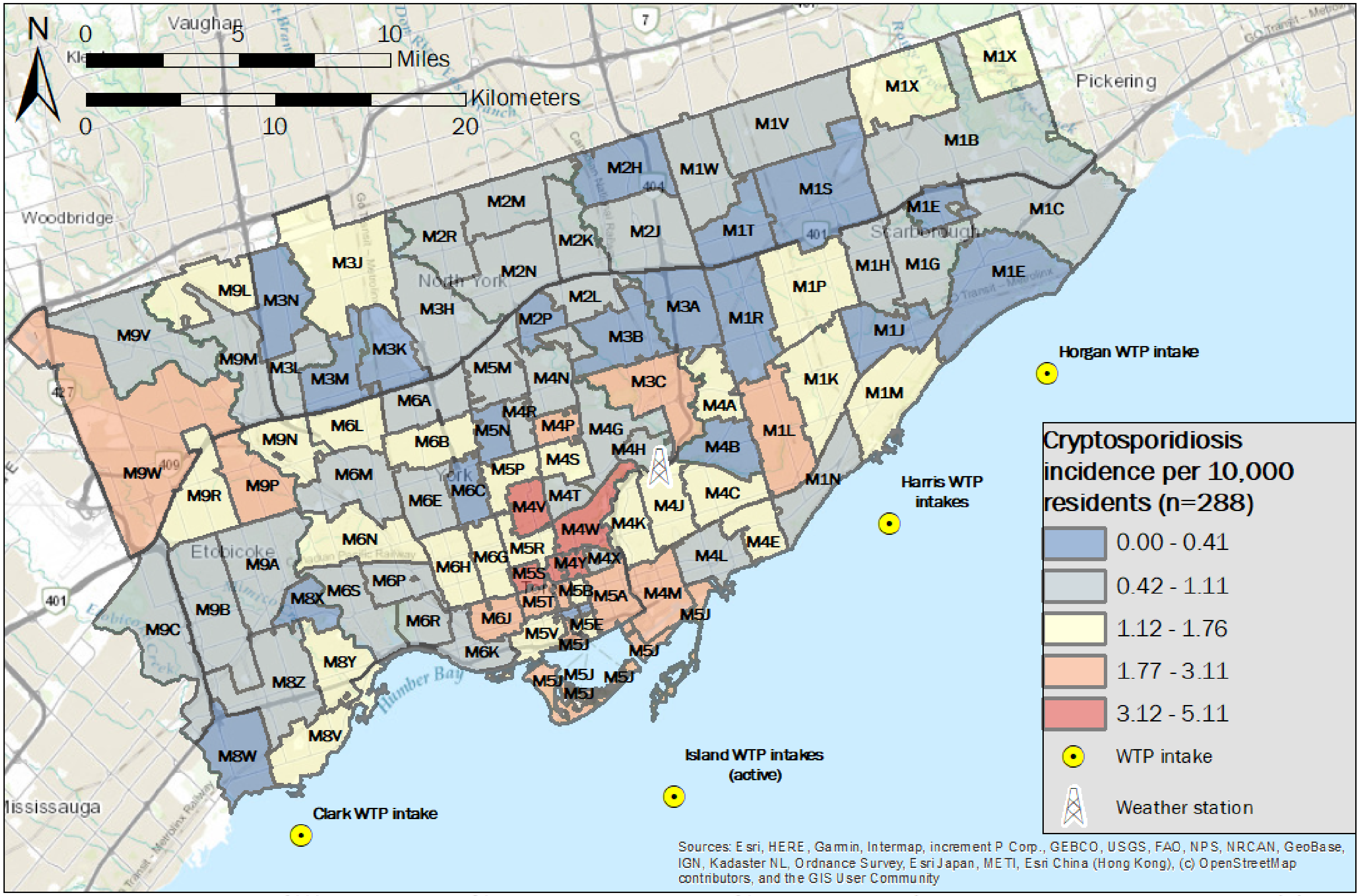
FSA	Cryptosporidiosis cases	Giardiasis cases	Combined AGI cases	Population (2011)	Population proportion	Cryptosporidiosis incidence	Giardiasis incidence	Combined AGI incidence
M5P	3	16	19	18,343	0.7%	1.64	8.72	10.36
M5R	4	33	37	25,056	1.0%	1.60	13.17	14.77
M5S	7	61	68	13,690	0.5%	5.11	44.56	49.67
M5T	4	30	34	18,705	0.7%	2.14	16.04	18.18
M5V	5	48	53	30,669	1.2%	1.63	15.65	17.28
M6A	2	11	13	19,754	0.8%	1.01	5.57	6.58
M6B	4	18	22	29,236	1.1%	1.37	6.16	7.52
M6C	1	15	16	24,256	0.9%	0.41	6.18	6.60
M6E	3	31	34	37,920	1.5%	0.79	8.18	8.97
M6G	4	47	51	32,075	1.2%	1.25	14.65	15.90
M6H	6	39	45	42,856	1.6%	1.40	9.10	10.50
M6J	9	34	43	28,949	1.1%	3.11	11.74	14.85
M6K	2	41	43	35,320	1.4%	0.57	11.61	12.17
M6L	3	13	16	20,807	0.8%	1.44	6.25	7.69
M6M	3	34	37	41,954	1.6%	0.72	8.10	8.82
M6N	6	28	34	41,312	1.6%	1.45	6.78	8.23
M6P	4	30	34	37,959	1.5%	1.05	7.90	8.96
M6R	1	27	28	19,439	0.7%	0.51	13.89	14.40
M6S	3	22	25	31,548	1.2%	0.95	6.97	7.92
M8V	5	28	33	31,921	1.2%	1.57	8.77	10.34
M8W	0	17	17	20,046	0.8%	0.00	8.48	8.48
M8X	0	12	12	10,481	0.4%	0.00	11.45	11.45
M8Y	3	16	19	19,805	0.8%	1.51	8.08	9.59
M8Z	1	13	14	15,302	0.6%	0.65	8.50	9.15
M9A	2	18	20	33,520	1.3%	0.60	5.37	5.97
M9B	2	10	12	30,182	1.2%	0.66	3.31	3.98
M9C	3	23	26	36,672	1.4%	0.82	6.27	7.09
M9L	2	18	20	11,998	0.5%	1.67	15.00	16.67
M9M	2	22	24	20,681	0.8%	0.97	10.64	11.60
M9N	3	25	28	24,946	1.0%	1.20	10.02	11.22
M9P	4	10	14	20,970	0.8%	1.91	4.77	6.68
M9R	5	40	45	32,581	1.2%	1.53	12.28	13.81
M9V	3	73	76	55,949	2.1%	0.54	13.05	13.58
M9W	8	29	37	41,164	1.6%	1.94	7.04	8.99
Totals	288	2,311	2,599	2,615,047	100%	1.10	8.84	9.94



Note: Health data are from January 1, 2009 through August 31, 2014. Population data are from the 2011 census (Statistics Canada).
The Toronto Water utility service area does not align with FSA boundaries.
Many FSAs within the utility service area extend beyond the service area where health data were also included.
Not all FSAs within the Toronto Water utility service area were included due to limited health data.

Author: Ryan C. Graydon
Date: 2020-04-06

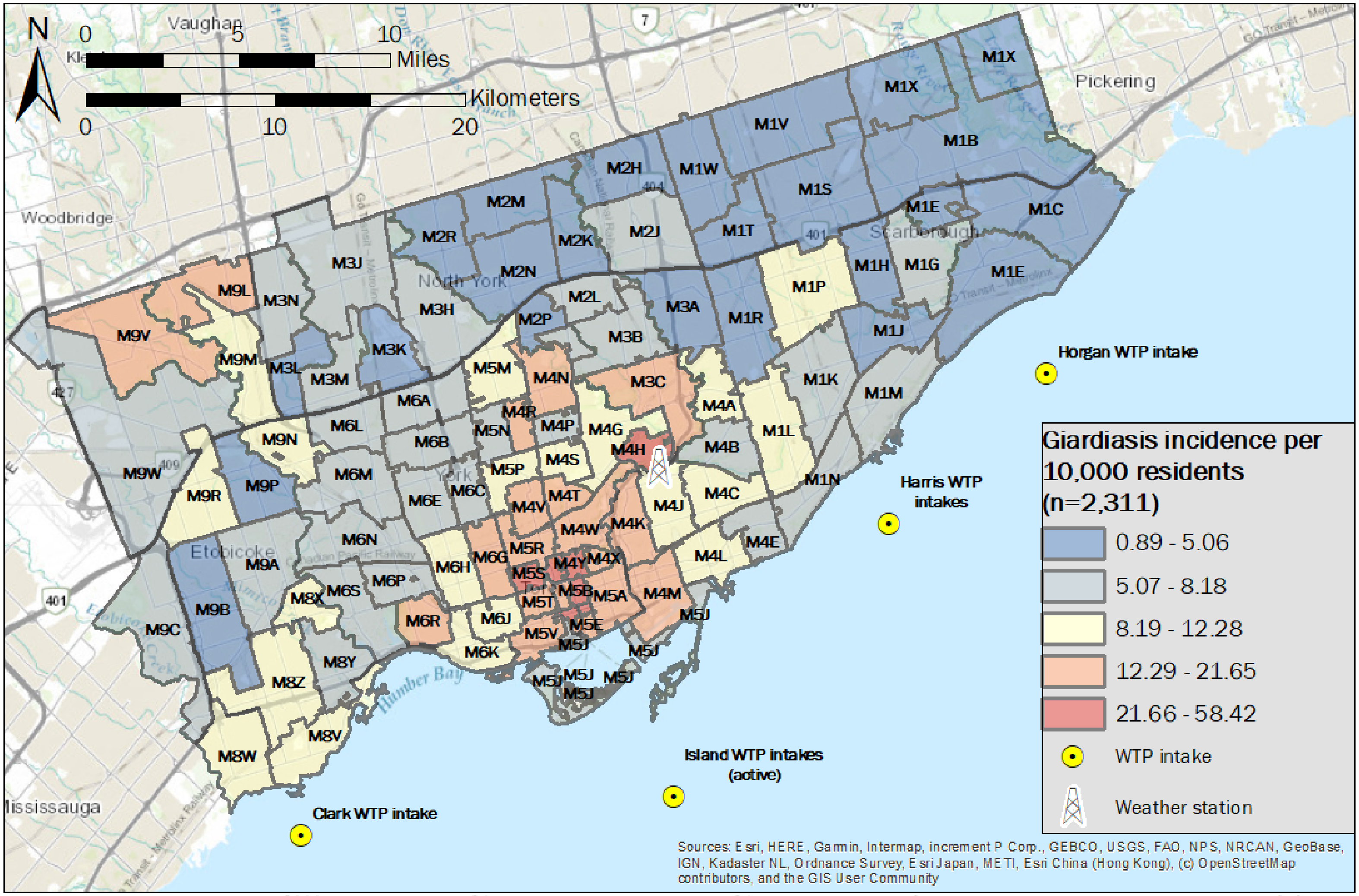
Figure 6-17: Toronto, Ontario combined AGI incidence by FSA. There were 288 cases of cryptosporidiosis (1.10 cases per 10,000 residents) and 2,311 cases of giardiasis (8.84 cases per 10,000 residents) for a total of 2,599 laboratory-confirmed cases of AGI (9.94 cases per 10,000 residents) from January 1, 2009 through August 31, 2014. The incidence per 10,000 residents was calculated from 2011 census data for each of the 96 FSAs (N=2,615,047) (Statistics Canada 2018).



Note: Health data are from January 1, 2009 through August 31, 2014. Population data are from the 2011 census (Statistics Canada).
The Toronto Water utility service area does not align with FSA boundaries.
Many FSAs within the utility service area extend beyond the service area where health data were also included.
Not all FSAs within the Toronto Water utility service area were included due to limited health data.

Author: Ryan C. Graydon
Date: 2020-04-06

Figure 6-18: Toronto, Ontario cryptosporidiosis incidence by FSA. There were 288 cases of cryptosporidiosis (1.10 cases per 10,000 residents) from January 1, 2009 through August 31, 2014. The incidence per 10,000 residents was calculated from 2011 census data for each of the 96 FSAs (N=2,615,047) (Statistics Canada 2018).



Note: Health data are from January 1, 2009 through August 31, 2014. Population data are from the 2011 census (Statistics Canada).
The Toronto Water utility service area does not align with FSA boundaries.
Many FSAs within the utility service area extend beyond the service area where health data were also included.
Not all FSAs within the Toronto Water utility service area were included due to limited health data.

Author: Ryan C. Graydon
Date: 2020-04-06

Figure 6-19: Toronto, Ontario giardiasis incidence by FSA. There were 2,311 cases of giardiasis (8.84 cases per 10,000 residents) from January 1, 2009 through August 31, 2014. The incidence per 10,000 residents was calculated from 2011 census data for each of the 96 FSAs (N=2,615,047) (Statistics Canada 2018).

6.3 Water treatment processes

Each water treatment plant follows the conventional process of coagulation and flocculation, sedimentation, filtration, disinfection, and fluoridation with some variation in the chemical inputs. The specific processes by water treatment plant are described here.

6.3.1 Green Bay Water Utility

The Green Bay Water Utility (GBWU) is charged with operating and planning improvements for the City's water supply system. In 2014, the estimated number of users served by the GBWU was 105,000. The average monthly water use was approximately 17.8 million gallons per day (MGD) (67,380 m^3/day). The average annual use was 6.5 billion gallons (24,605,000 m^3) (see **Table 2-2**) (personal communication, Russ Hardwick - Green Bay Water Utility, April 21, 2020).

Major components of the existing water treatment and supply facilities for the City of Green Bay are summarized as follows:

- **Lake Michigan Intake Pipes**: Water is withdrawn from the lake by gravity through two 42-inch (1.07-meter) diameter intake lines. The first pipe is 6,000 feet (1.8 kilometers) long and was constructed in 1955. The second pipe is 3,000 feet (0.91 kilometers) long and was constructed in 1968. Together the intake pipes have a capacity of 60 MGD (227,000 m^3/day).
- **Raw Water Pumping Station (Lake Station)**: Water is pumped into the Raw Water Transmission Main using six pumps that range from 600 to 800 horsepower each. Each pump has a capacity of 8 MGD (30,283 m^3/day).
- **Raw Water Transmission Main**: One 42-inch (1.07-meter) main transmits water between the lake and the water treatment plant. This length of the main is approximately 14.6 miles (23.5 kilometers). The capacity of this main ranges from 23.5 to 42 MGD. (89,000 to 159,000 m^3/day).
- **Raw Water Booster Station**: The raw water booster station consists of two 1,750 horsepower pumps, one with a 35 MGD (132,500 m^3/day) capacity and one with a 37 MGD capacity (140,060 m^3/day). There is a 1,000,000-gallon (3,785-cubic meter) reservoir at the booster station site.
- **Water Treatment Plant**: The capacity of the water treatment plant is 42 MGD (159,000 m^3/day).
- **Treated Water Transmission Mains**: Two treated water transmission mains leave the plant. One transmission main is located on the north side of Finger Road and the other is located on the south side of the road. Both are prestressed concrete and are 36 inches (0.91 meters) in diameter.

The distribution system is divided into nine separate pressure zones. Within each pressure zone is an integrated system consisting of pressure reducing valves, booster pumps, elevated storage tanks, ground reservoirs, smaller diameter water mains and service connections. The GBWU maintains nine groundwater wells. These wells are maintained to provide excess capacity during seasonal peaks and for backup.[1]

During the study period of 2009 to 2014 and at the time of publication, Green Bay Water follows this water treatment process (personal communication, Russ Hardwick - Green Bay Water Utility, December 17, 2019):

i. raw water is obtained at the intake one mile (1.6 kilometers) offshore of Kewaunee in Lake Michigan at a depth of 60 feet (18.3 meters)
ii. chlorine gas is added at the intake for zebra mussel control
iii. ozonation
iv. coagulation – polyaluminum hydroxychloride
v. sedimentation
vi. filtration using dual media: anthracite and sand
vii. disinfection – free chlorine by addition of sodium hypochlorite
viii. fluoridation

6.3.2 Hamilton Water

Lake water enters an intake pipe and is pumped to the Woodward Avenue Water Treatment Facility. The water treatment process includes:

i. pre-chlorination
ii. screening
iii. clarification by means of coagulation with polyaluminum chloride
iv. flocculation by mechanical mixing
v. sedimentation
vi. filtration using granulated activated carbon in the filters to remove taste and odour
vii. chlorine and ammonia added to the filtered water to bring the combined chlorine residual to approximately 2.2 - 2.5 milligrams per litre
viii. hydrofluosilicic acid (fluoride) added to the drinking water to promote dental health

The water treatment plant has a rated capacity of 909,000 cubic meters per day (200 MGD) and operates between one quarter and one third of its capacity (City of Hamilton 2019).

6.3.3 Milwaukee Water Works

Milwaukee Water Works provides potable water to nearly 867,000 people in 16 communities in Milwaukee, Ozaukee and Waukesha counties.[2] Milwaukee Water Works treats Lake Michigan water at the Linnwood Water Treatment Plant on the north side and the Howard Avenue Water Treatment Plant on the south side. The Linnwood intake is 1.25 miles (2.0 kilometers) from the

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[1] Public Utilities Analysis: Green Bay Smart Growth 2022. Green Bay Water Utility. May 2003. Accessed at: greenbaywi.gov/DocumentCenter/View/1281/Public-Utilities-PDF, November 1, 2019.
[2] About the Milwaukee Water Works. City of Milwaukee. Accessed at: city.milwaukee.gov/water/about#.Xp3AvJkpCCQ, December 16, 2019.

shore at a depth of 60 feet (18.3 meters). The Texas Avenue intake supplying the Howard Avenue Water Treatment Plant is 2.5 miles (4.0 kilometers) offshore at a depth of 60 feet (18.3 meters). The two intakes combined draw an average of 103 MGD (390,000 m^3/day). The Milwaukee Water Works practical capacity is 360 MGD (1,362,000 m^3/day). The total water sales in 2014 was 29.9 billion gallons (113,133,000 m^3) (see **Table 2-2**).

The lake water passes through a multiple barrier treatment process to protect public health. The barriers destroy and remove illness-causing microorganisms in the lake water. The primary form of disinfection is ozone gas. Ozone generators spark liquid oxygen, O_2, with electricity to create ozone gas, O_3. In the first stage of water treatment (**Figure 6-20**), ozone is bubbled into the water in large contactor tanks. Ozone attacks illness-causing microorganisms and breaks apart harmful compounds at the atomic level. With its three oxygen atoms, ozone is unstable and highly reactive. It readily gives up one atom to the carbon in the membranes of microbes. Ozone destroys illness-causing microorganisms such as cryptosporidium and giardia. Ozone breaks apart compounds that can cause taste and odor. Using ozone as a disinfectant reduces the formation of disinfection byproducts.

Particles in the water are then removed through coagulation, flocculation, settling and biologically active filtration. Chlorine is added as a secondary disinfectant. Fluoride is added to reduce dental cavities. A phosphorous compound is added to control pipe corrosion to prevent lead that may be present in pipes from leaching into the water. Finally, chloramine disinfection maintains a residual in the distribution system to protect against bacterial contamination. The Wisconsin Department of Natural Resources requires water utilities to maintain a detectable level of disinfectant throughout the distribution system to maintain bacteriological protection.

All chemicals that are added are certified food grade, safe for human consumption. The Supervisory Control and Data Acquisition System at both treatment plants provides real-time data from chemical feed systems, including ozone, and all water quality monitoring as well as control of water pumping stations and the distribution system.[3]

[3] Water Treatment. City of Milwaukee. Accessed at: city.milwaukee.gov/water/about/WaterTreatment#.Xp3CcJkpCCR, December 16, 2019.

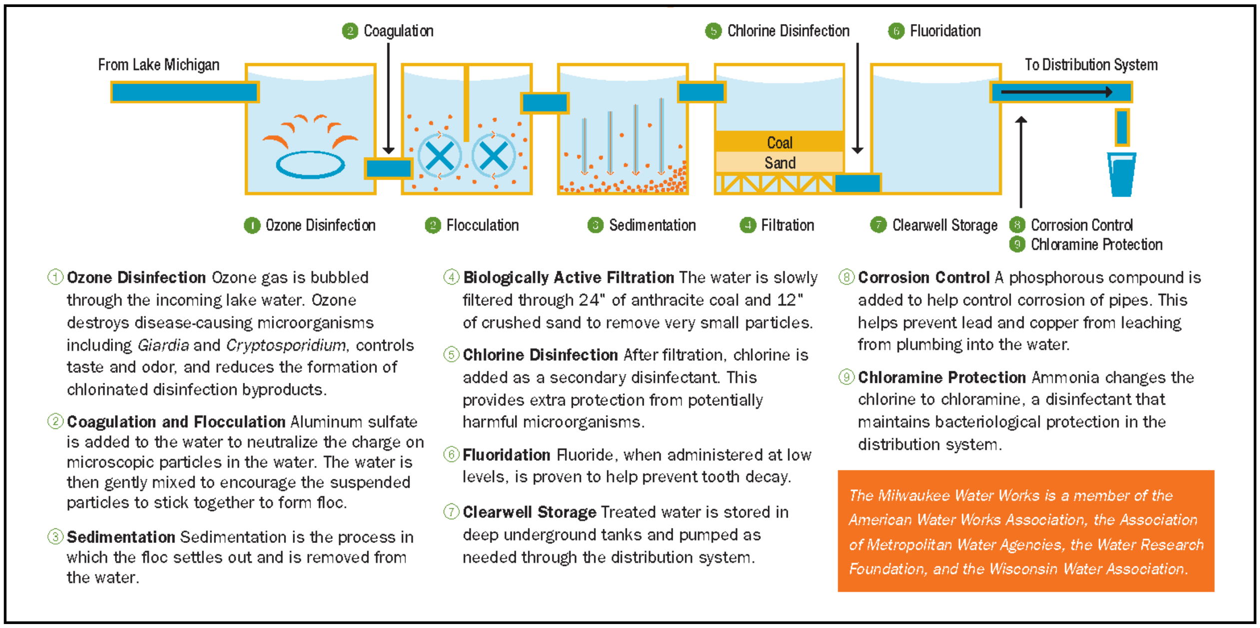

Figure 6-20: Milwaukee Water Works drinking water treatment process.

6.3.4 Toronto Water

Toronto Water has four water treatment plants that utilize slightly different treatment processes (personal communication, Emily Zegers - Toronto Water, December 18, 2019).

Harris Water Treatment Plant

i. pre-chlorination
ii. screening
iii. coagulation with Alum (Aluminum sulphate)
iv. sedimentation basins upstream of filters
v. filtration[4] using dual media: anthracite and sand
vi. chlorine (for disinfection)
vii. sulphur dioxide (for de-chlorination)
viii. hydrofluosilicic acid (for fluoridation)
ix. aqueous ammonia (for chloramination)

[4] "Filtration" has sedimentation basins before the water goes to the filters due to the intakes' close proximities to the shore (personal communication, William Fernandes - Toronto Water, April 8, 2020). Clark's intake is 1.6 kilometers (1.0 mile) offshore and Harris' intakes are 2.2 kilometers (1.4 miles) offshore (see **Table 2-2**).

Horgan Water Treatment Plant

i. pre-chlorination
ii. ozonation (started in 2013- for disinfection and taste and odor control)
iii. sodium bisulphite (started in 2013)
iv. polymer - cationic (Magnafloc LT 7996) (started in 2013)
v. coagulation with alum (aluminum sulphate) or polyaluminum chloride (PACL - SternPAC)
vi. direct filtration[5] using dual media: anthracite and sand
vii. chlorine (for disinfection)
viii. sulphur dioxide (for de-chlorination)
ix. hydrofluosilicic acid (for fluoridation)
x. aqueous ammonia (for chloramination)

Island Water Treatment Plant

i. pre-chlorination
ii. screening
iii. coagulant dosing - polyaluminum chloride (PACl)
iv. direct filtration[5] using dual media: anthracite and sand
v. chlorination followed by chorine contact tanks
vi. sulphur dioxide (for de-chlorination)
vii. sodium bisulphite (for de-chlorination)
viii. aqua ammonia addition
ix. hydrofluosilicic acid addition

Clark Water Treatment Plant

i. pre-chlorination
ii. screening
iii. coagulation with alum (aluminum sulphate)
iv. sedimentation basins
v. filtration[4] using dual media: anthracite and sand
vi. chlorine (for disinfection)
vii. sulphur dioxide (for de-chlorination)
viii. hydrofluosilicic acid (for fluoridation)
ix. aqueous ammonia (for chloramination)

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[5] "Direct filtration" means there are no sedimentation basins prior to filtration due to the intakes' far distances offshore (personal communication, William Fernandes - Toronto Water, April 8, 2020). Horgan's intake is 2.9 kilometers (1.8 miles) offshore and Island's intakes are 4.8 kilometers (3.0 miles) offshore (see Table 2-2).

6.4 Seasonality of AGI cases

The distribution of cryptosporidiosis and giardiasis cases by year and season are shown in the following figures. The seasons were defined as:

- Winter: December, January, February
- Spring: March, April, May
- Summer: June, July, August
- Fall: September, October, November

Because the study period was January 1, 2009 through August 31, 2014, three months of fall data (Sept, Oct, Nov 2014) and one month of winter data (Dec 2014) are not included.

6.4.1 Green Bay, Wisconsin

As shown in Figure 3-1, there were 99 cases of cryptosporidiosis (4.27 cases per 10,000 residents) and 93 cases of giardiasis (4.01 cases per 10,000 residents) for a total of 192 laboratory-confirmed cases of AGI (8.28 cases per 10,000 residents) from January 1, 2009 through August 31, 2014. Figure 6-21shows the seasonality of AGI cases in the Green Bay Water Utility service area. The highest seasonal cases occurred in summer 2010 (23 combined AGI cases) followed by fall 2013 (21 combined AGI cases). See Figure 3-2 for boxplots of weekly combined AGI cases, grouped by months.

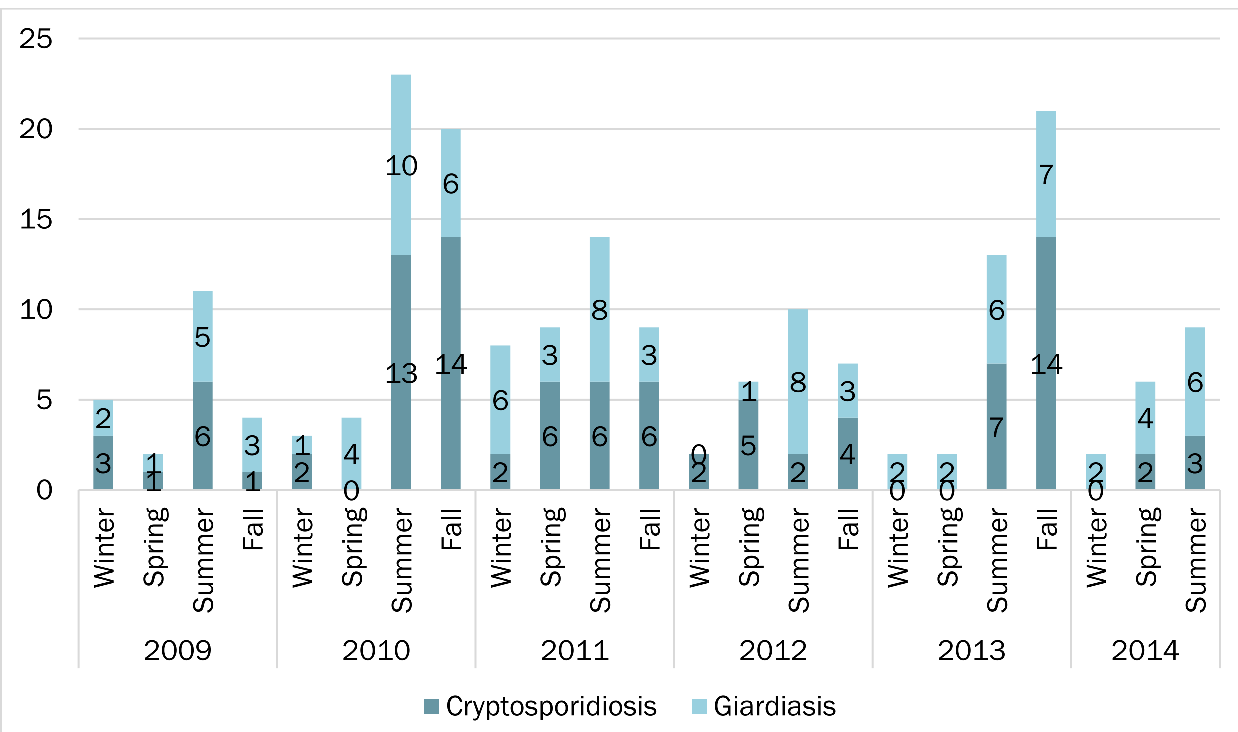

Figure 6-21: Seasonality of AGI cases in Green Bay, Wisconsin, winter 2009 to summer 2014.

6.4.2 Hamilton, Ontario

As shown in **Figure 3-1**, there were 36 cases of cryptosporidiosis (0.70 cases per 10,000 residents) and 265 cases of giardiasis (5.14 cases per 10,000 residents) for a total of 301 laboratory-confirmed cases of AGI (5.84 cases per 10,000 residents) from January 1, 2009 through August 31, 2014. **Figure 6-22** shows the seasonality of AGI cases in the Hamilton Water utility service area. The highest seasonal cases occurred in summer 2009 (23 combined AGI cases) followed by summer 2013 and summer 2014 (22 combined AGI cases). See **Figure 3-2** for boxplots of weekly combined AGI cases, grouped by months.

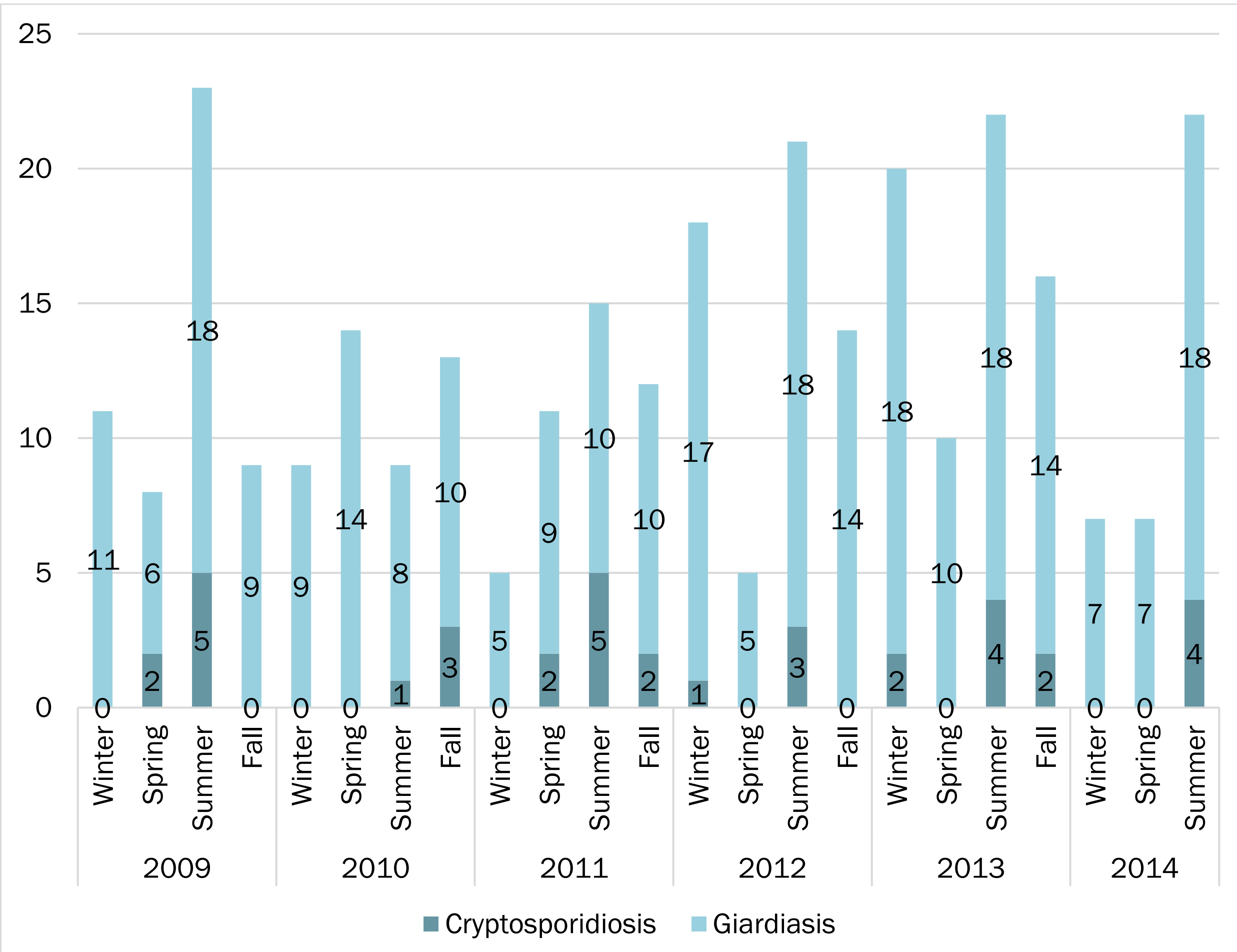

Figure 6-22: Seasonality of AGI cases in Hamilton, Ontario winter 2009 to summer 2014.

6.4.3 Milwaukee, Wisconsin

As shown in **Figure 3-1**, there were 122 cases of cryptosporidiosis (1.41 cases per 10,000 residents) and 577 cases of giardiasis (6.68 cases per 10,000 residents) for a total of 699 laboratory-confirmed cases of AGI (8.09 cases per 10,000 residents) from January 1, 2009 through August 31, 2014. **Figure 6-23** shows the seasonality of AGI cases in the Milwaukee Water Works utility service area. The highest seasonal cases occurred in fall 2010 (46 combined AGI cases) followed by summer 2011 (44 combined AGI cases). See **Figure 3-2** for boxplots of weekly combined AGI cases, grouped by months.

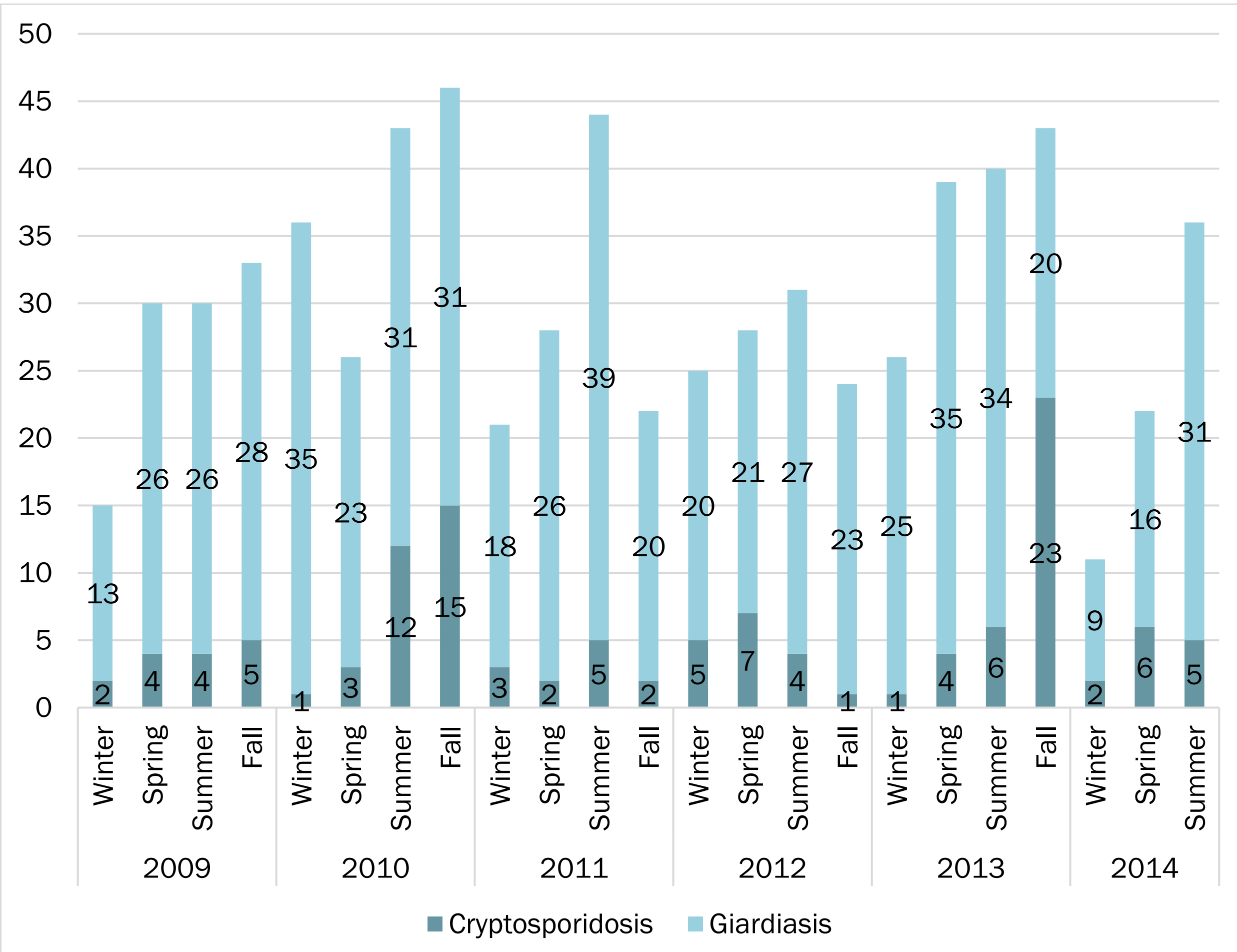

Figure 6-23: Seasonality of AGI cases in Milwaukee, Wisconsin winter 2009 to summer 2014.

6.4.4 Toronto, Ontario

As shown in **Figure 3-1**, there were 288 cases of cryptosporidiosis (1.10 cases per 10,000 residents) and 2,311 cases of giardiasis (8.84 cases per 10,000 residents) for a total of 2,599 laboratory-confirmed cases of AGI (9.94 cases per 10,000 residents) from January 1, 2009 through August 31, 2014. **Figure 6-24** shows the seasonality of AGI cases in the Toronto Water utility service area. The highest seasonal cases occurred in summer 2014 (156 combined AGI cases) followed by summer 2009 (154 combined AGI cases). See **Figure 3-2** for boxplots of weekly combined AGI cases, grouped by months.

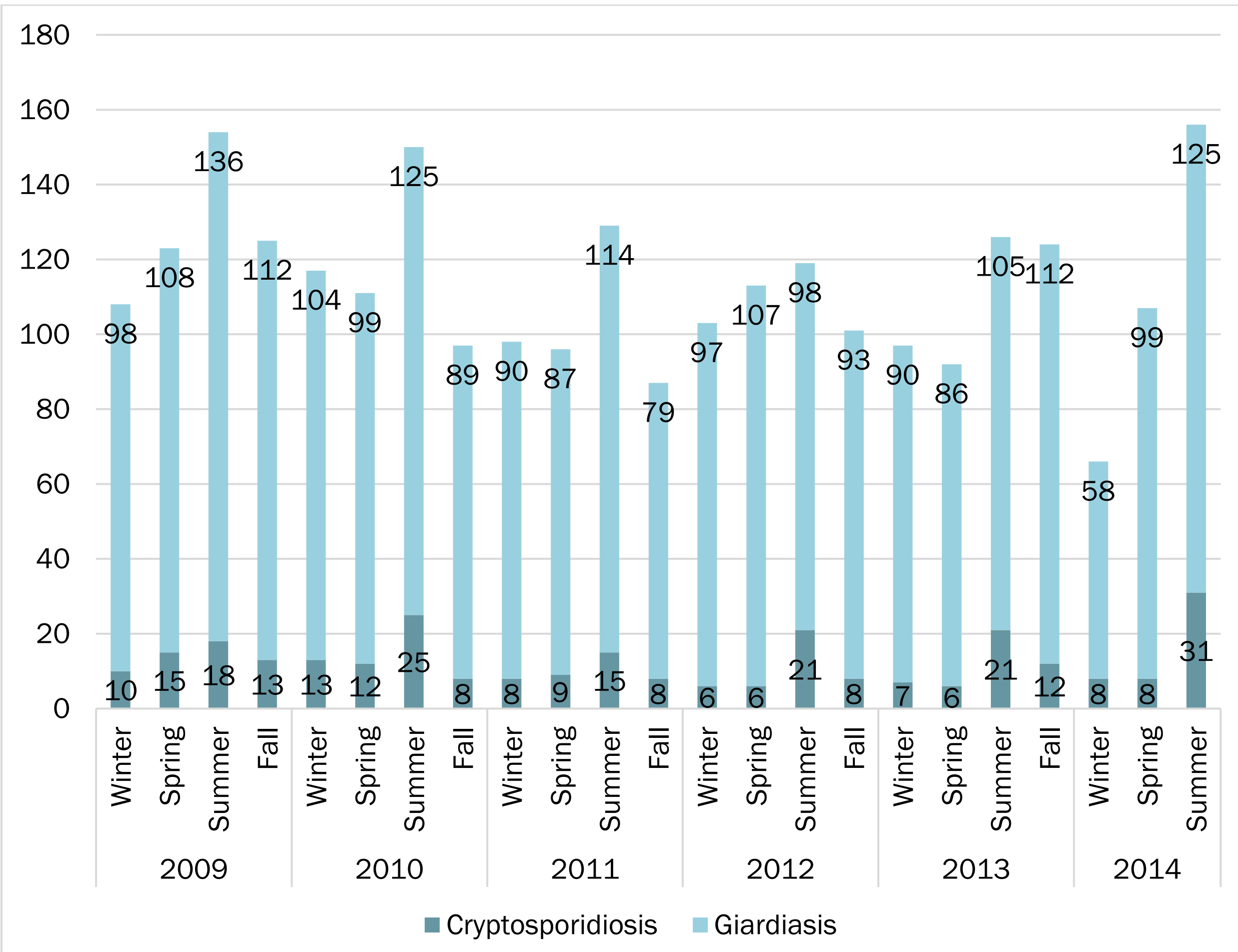

Figure 6-24: Seasonality of AGI cases in Toronto, Ontario winter 2009 to summer 2014.

6.5 Weather and raw water indicators

The following show the definition of the precipitation pattern (dry/wet factor), time series of dry days, cumulative weekly precipitation, extreme precipitation weeks, and weekly mean raw water turbidity and total coliforms for each city.

6.5.1 Precipitation pattern

Because the climate classification for these four Great Lakes cities (Dfb: snow, fully humid, warm summer) is different than Vancouver's climate classification (Csb: warm temperate, summer dry, warm summer), the definition of precipitation pattern (dry or wet periods) used in this study was determined by the weather data for each of the case cities. To be consistent with the methods used by Chhetri and colleagues (2017), we sought to replicate Vancouver's even split of dry week and wet weeks. The best fit for each city was to define Green Bay and Milwaukee less than or equal to 40 days of no precipitation in the preceding 60 days as dry and Hamilton and Toronto less than or equal to 35 days of no precipitation in the preceding 60 days as dry. Dry weeks were defined as the minimum number of dry days in a week.

The results of the number and proportion of dry weeks and wet weeks for less than or equal to 30, less than or equal to 35, and less than or equal to 40 dry days (days with no precipitation) in the preceding 60 days for each case city and the reference case are shown in **Table 6-7**. See below for each city's figures showing the time series of dry days with the cutoff at 30, 35, and 40 dry days (days with no precipitation) in the preceding 60 days.

Table 6-7: Comparison of precipitation patterns' definitions for all four case cities and the reference case. The green outline shows which definition of dry days most closely results in a 50/50 distribution of dry weeks and wet weeks, and was thus selected for our methods.

# Dry Days in Preceding 60 Days		≤30	≤35	≤40
Green Bay, Wisconsin Kewaunee weather station Jan 1, 2009 - Aug 31, 2014 (296 weeks)	Wet Weeks	0	23	**91**
	Wet %	0%	8%	**31%**
	Dry Weeks	296	273	**205**
	Dry %	100%	92%	**69%**
Hamilton, Ontario Hamilton A weather station Jan 1, 2009 - Aug 31, 2014 (296 weeks)	Wet Weeks	77	**162**	254
	Wet %	26%	**55%**	86%
	Dry Weeks	219	**134**	42
	Dry %	74%	**45%**	14%
Milwaukee, Wisconsin Milwaukee Mitchell International Airport weather station Jan 1, 2009 - Aug 31, 2014 (296 weeks)	Wet Weeks	26	64	**171**
	Wet %	9%	22%	**58%**
	Dry Weeks	270	232	**125**
	Dry %	91%	78%	**42%**
Toronto, Ontario Toronto East York Dustan weather station Jan 1, 2009 - Aug 31, 2014 (296 weeks)	Wet Weeks	56	**147**	247
	Wet %	19%	**50%**	83%
	Dry Weeks	240	**149**	49
	Dry %	81%	**50%**	17%
Vancouver, British Columbia Jan 1, 1997 - Dec 31, 2009 (679 weeks) From Chhetri et al. (2017)	Wet Weeks	339		
	Wet %	50%		
	Dry Weeks	340		
	Dry %	50%		

6.5.2 Green Bay, Wisconsin

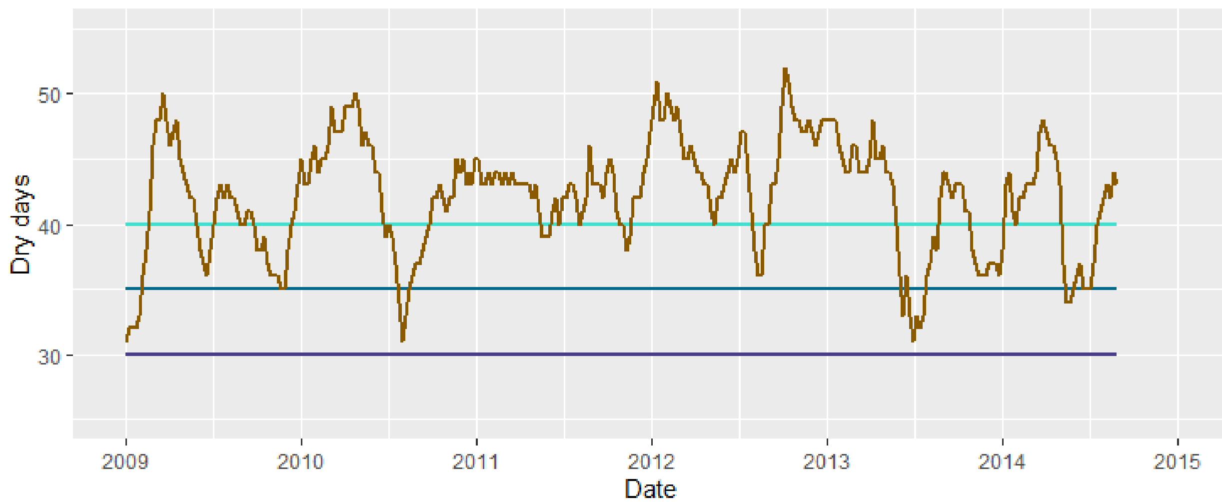

Figure 6-25: Green Bay, Wisconsin weekly time series of number of dry days in the preceding 60 days, from January 1, 2009 through August 31, 2014 (296 weeks). The purple line indicates the 30-day threshold. The blue line indicates the 35-day threshold. The turquoise line indicates the 40-day threshold. Points above the lines were classified as dry periods and points below the lines were classified as wet periods. See Table 6-7 for number and proportions for each dry/wet threshold.

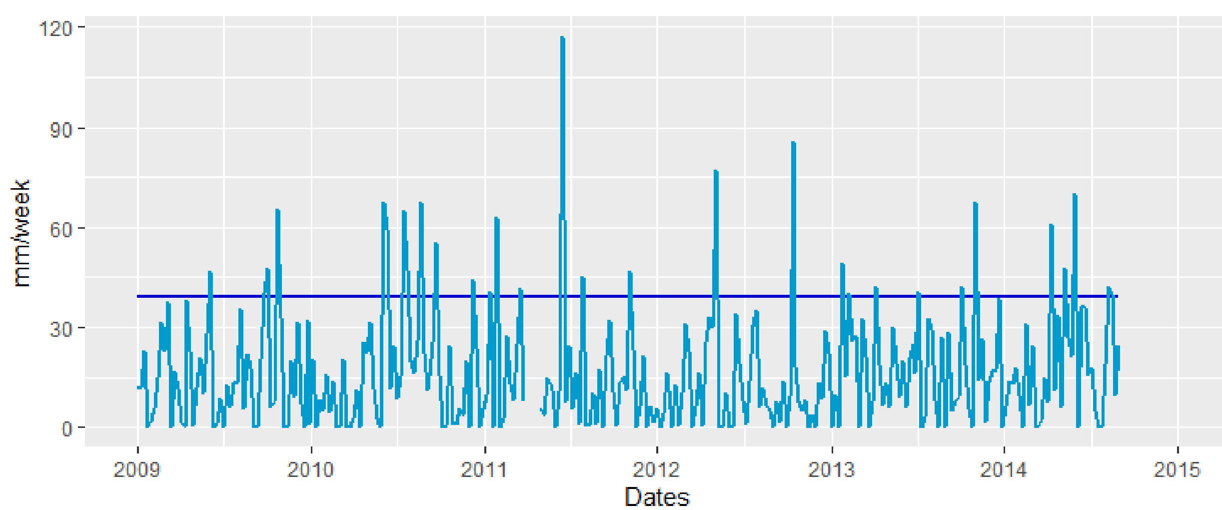

Figure 6-26: Green Bay, Wisconsin weekly time series of precipitation. Purple line indicates the weekly cumulative precipitation 90th percentile of 39.4 mm. Points above the purple line were classified as extreme precipitation weeks.

Table 6-8: Green Bay, Wisconsin extreme precipitation weeks. An extreme precipitation week had precipitation that exceeded the 90th percentile for the study period. For Green Bay, Wisconsin the 90th percentile for cumulative weekly precipitation was 39.4 mm. There were 30 extreme event weeks (formula included zero values in the dataset).

90th percentile precipitation weeks		
2009-06-04 - 2009-06-10	2011-01-13 - 2011-01-19	2013-01-24 - 2013-01-30
2009-09-24 - 2009-09-30	2011-01-27 - 2011-02-02	2013-02-07 - 2013-02-13
2009-10-01 - 2009-10-07	2011-03-17 - 2011-03-23	2013-04-04 - 2013-04-10
2009-10-22 - 2009-10-28	2011-06-16 - 2011-06-22	2013-07-04 - 2013-07-10
2010-06-03 - 2010-06-09	2011-07-28 - 2011-08-03	2013-10-03 - 2013-10-09
2010-06-10 - 2010-06-16	2011-11-03 - 2011-11-09	2013-10-31 - 2013-11-06
2010-07-15 - 2010-07-21	2012-05-03 - 2012-05-09	2014-04-10 - 2014-04-16
2010-07-22 - 2010-07-28	2012-10-11 - 2012-10-17	2014-05-08 - 2014-05-14
2010-08-19 - 2010-08-25		2014-05-29 - 2014-06-04
2010-09-23 - 2010-09-29		2014-08-07 - 2014-08-13
2010-12-09 - 2010-12-15		2014-08-14 - 2014-08-20

Based on a precipitation pattern definition of 40 days of no precipitation in the preceding 60 days as dry (**Table 6-7** and **Figure 6-25**), the font color indicates if the extreme precipitation event occurred during a wet precipitation pattern (n=13) or dry precipitation pattern (e.g., abrupt precipitation spike) (n=17).

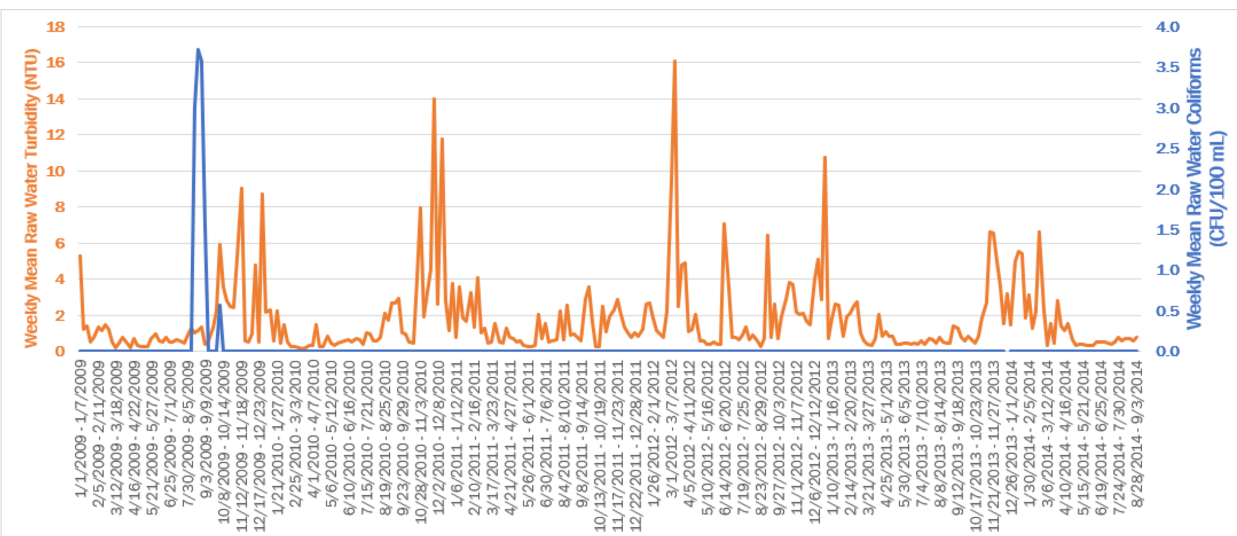

Figure 6-27: Green Bay, Wisconsin raw water turbidity and total coliforms.

6.5.3 Hamilton, Ontario

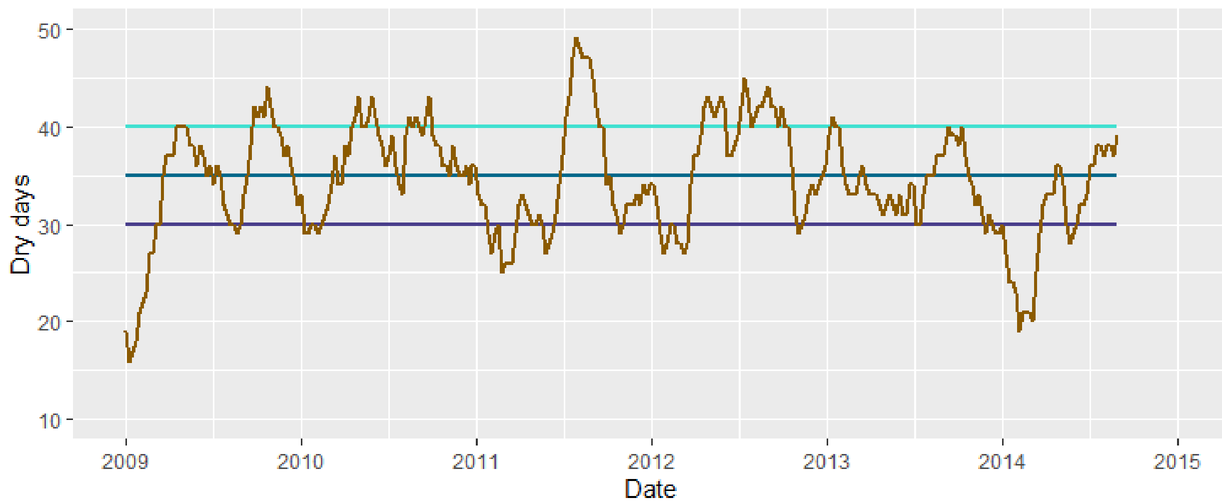

Figure 6-28: Hamilton, Ontario weekly time series of the number of dry days in the preceding 60 days, from January 1, 2009 through August 31, 2014 (296 weeks). The purple line indicates the 30-day threshold. The blue line indicates the 35-day threshold. The turquoise line represents the 40-day threshold. Points above the lines were classified as dry periods and points below the lines were classified as wet periods. See Table 6-7 for number and proportions for each dry/wet threshold.

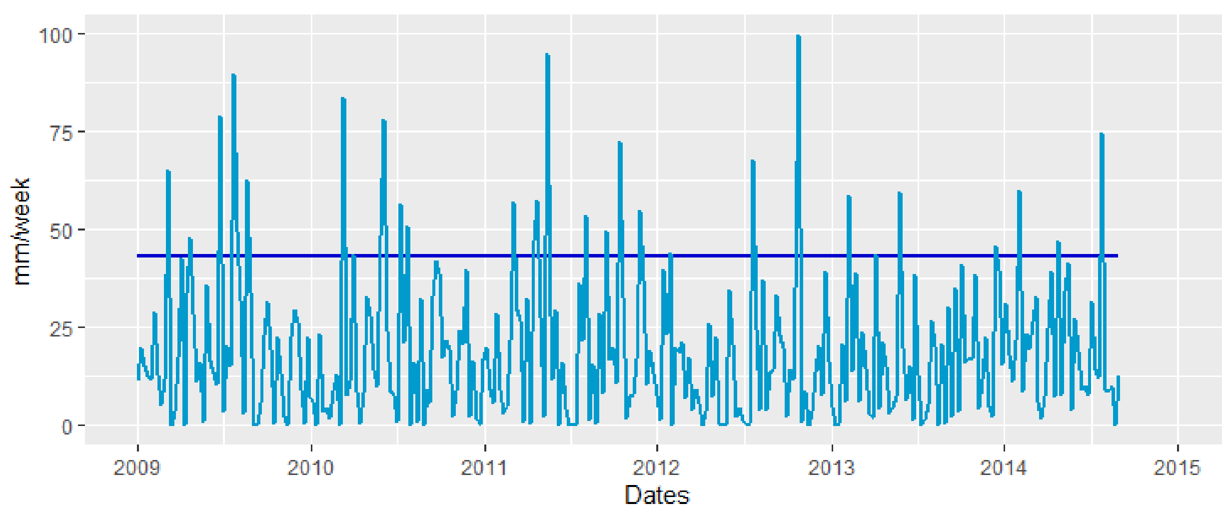

Figure 6-29: Hamilton, Ontario weekly time series of precipitation. Purple line indicates the weekly cumulative precipitation 90th percentile of 43.4 mm. Points above the purple line were classified as extreme precipitation weeks.

Table 6-9: Hamilton, Ontario extreme precipitation weeks. An extreme precipitation week had precipitation that exceeded the 90th-percentile for the study period. For Hamilton, the 90th percentile for cumulative weekly precipitation was 43.4 mm. There were 30 extreme event weeks (formula included zero values in the dataset).

90th percentile precipitation weeks		
2009-03-05 - 2009-03-11	2011-03-03 - 2011-03-09	2013-02-07 - 2013-02-13
2009-04-23 - 2009-04-29	2011-04-14 - 2011-04-20	2013-04-04 - 2013-04-10
2009-06-25 - 2009-07-01	2011-04-21 - 2011-04-27	2013-05-23 - 2013-05-29
2009-07-23 - 2009-07-29	2011-05-12 - 2011-05-18	2013-12-12 - 2013-12-18
2009-07-30 - 2009-08-05	2011-08-04 - 2011-08-10	2014-01-30 - 2014-02-05
2009-08-20 - 2009-08-26	2011-09-15 - 2011-09-21	2014-04-24 - 2014-04-30
2010-03-11 - 2010-03-17	2011-10-13 - 2011-10-19	2014-07-24 - 2014-07-30
2010-04-01 - 2010-04-07	2011-11-24 - 2011-11-30	
2010-05-27 - 2010-06-02	2012-01-26 - 2012-02-01	
2010-06-03 - 2010-06-09	2012-07-19 - 2012-07-25	
2010-07-08 - 2010-07-14	2012-10-25 - 2012-10-31	
2010-07-22 - 2010-07-28		

Based on a precipitation pattern definition of 35 days of no precipitation in the preceding 60 days as dry (**Table 6-7** and **Figure 6-25**), the font color indicates if the extreme precipitation event occurred during a wet precipitation pattern (n=18) or dry precipitation pattern (e.g., abrupt precipitation spike) (n=12).

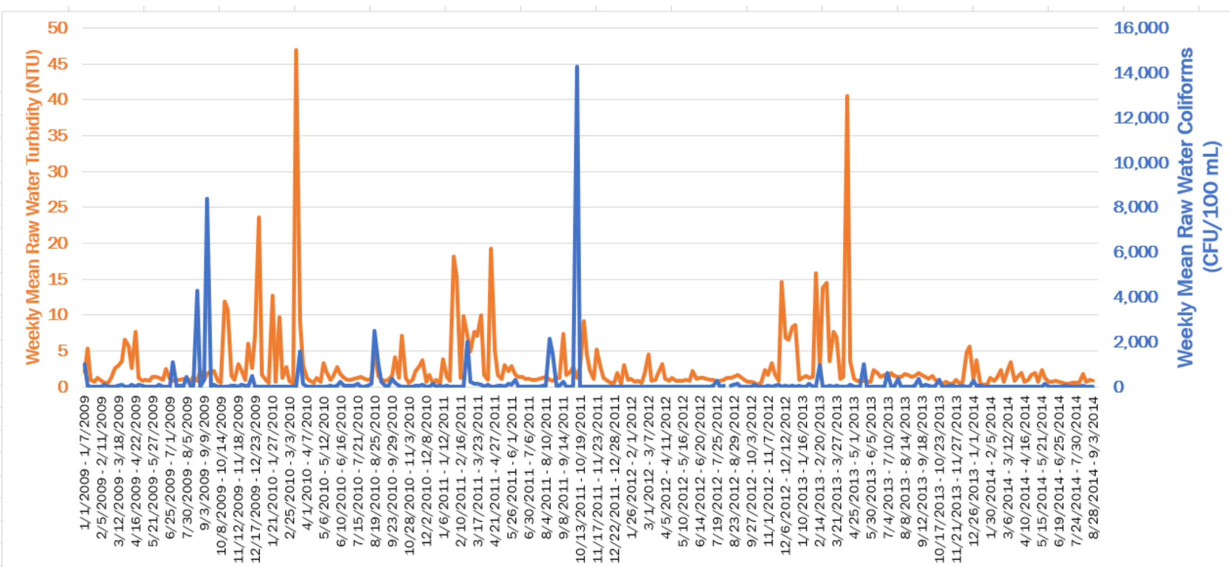

Figure 6-30: Hamilton, Ontario raw water turbidity and total coliforms.

6.5.4 Milwaukee, Wisconsin

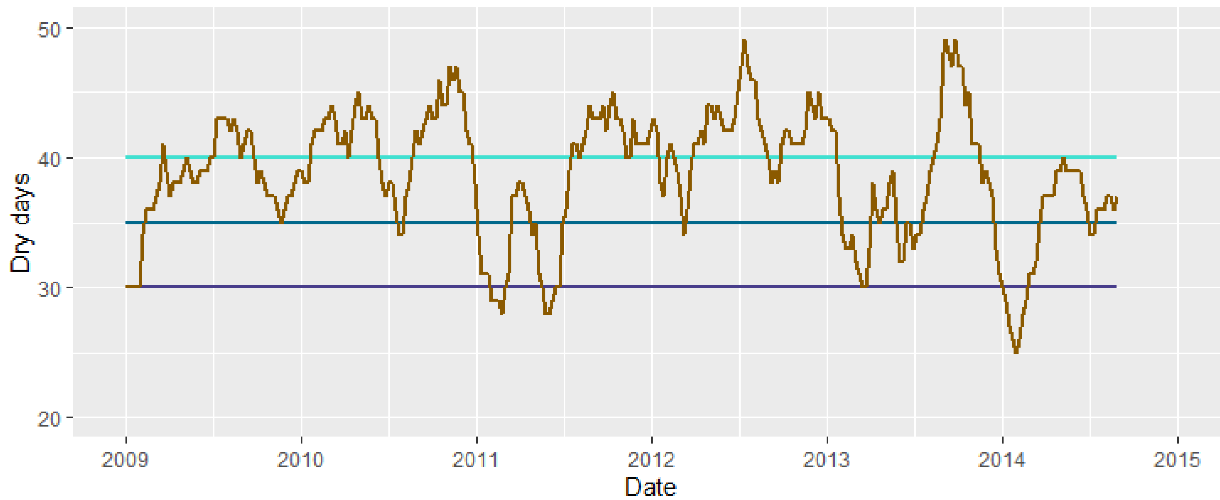

Figure 6-31: Milwaukee, Wisconsin weekly time series of the number of dry days in the preceding 60 days, from January 1, 2009 through August 31, 2014 (296 weeks). The purple line indicates the 30-day threshold. The blue line indicates the 35-day threshold. The turquoise line represents the 40-day threshold. Points above the lines were classified as dry periods and points below the lines were classified as wet periods. See Table 6-7 for number and proportions for each dry/wet threshold.

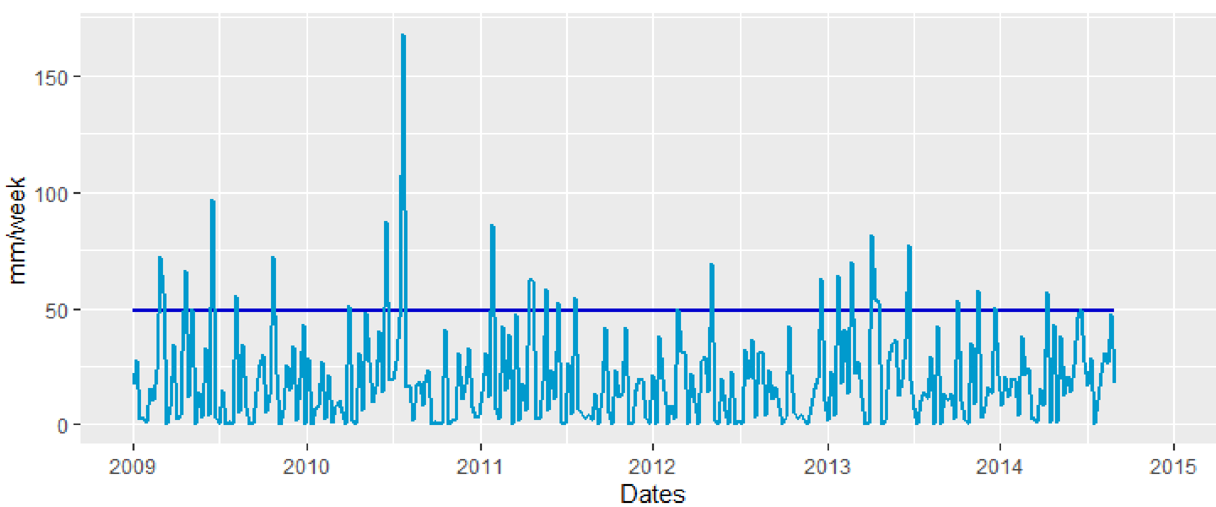

Figure 6-32: Milwaukee, Wisconsin weekly time series of precipitation. Purple line indicates the weekly cumulative precipitation 90th percentile of 48.9 mm. Points above the purple line were classified as extreme precipitation weeks.

Table 6-10: Milwaukee, Wisconsin extreme precipitation weeks. An extreme precipitation week had precipitation that exceeded the 90th percentile for the study period. For Milwaukee, the 90th percentile for cumulative weekly precipitation was 48.9 mm. There were 30 extreme event weeks (formula included zero values in the dataset).

90th percentile precipitation weeks		
2009-02-26 - 2009-03-04	2011-01-27 - 2011-02-02	2013-01-24 - 2013-01-30
2009-03-05 - 2009-03-11	2011-04-14 - 2011-04-20	2013-02-21 - 2013-02-27
2009-04-23 - 2009-04-29	2011-04-21 - 2011-04-27	2013-04-04 - 2013-04-10
2009-05-07 - 2009-05-13	2011-05-19 - 2011-05-25	2013-04-11 - 2013-04-17
2009-06-18 - 2009-06-24	2011-06-16 - 2011-06-22	2013-04-18 - 2013-04-24
2009-08-06 - 2009-08-12	2011-07-21 - 2011-07-27	2013-06-20 - 2013-06-26
2009-10-22 - 2009-10-28	2012-02-23 - 2012-02-29	2013-10-03 - 2013-10-09
2010-04-01 - 2010-04-07	2012-05-03 - 2012-05-09	2013-11-14 - 2013-11-20
2010-06-17 - 2010-06-23	2012-12-20 - 2012-12-26	2013-12-19 - 2013-12-25
2010-07-22 - 2010-07-28		2014-04-10 - 2014-04-16
		2014-06-19 - 2014-06-25

Based on a precipitation pattern definition of 40 days of no precipitation in the preceding 60 days as dry (Table 6-7 and Figure 6-31), the font color indicates if the extreme precipitation event occurred during a wet precipitation pattern (n=23) or dry precipitation pattern (e.g., abrupt precipitation spike) (n=7).

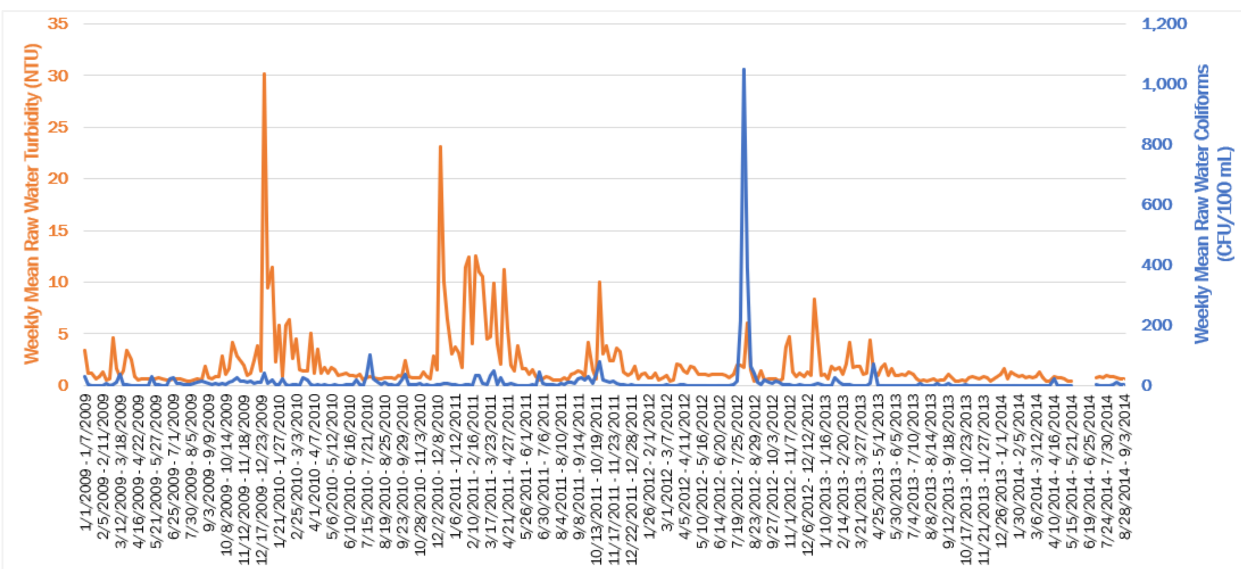

Figure 6-33: Milwaukee, Wisconsin Howard raw water turbidity and total coliforms.

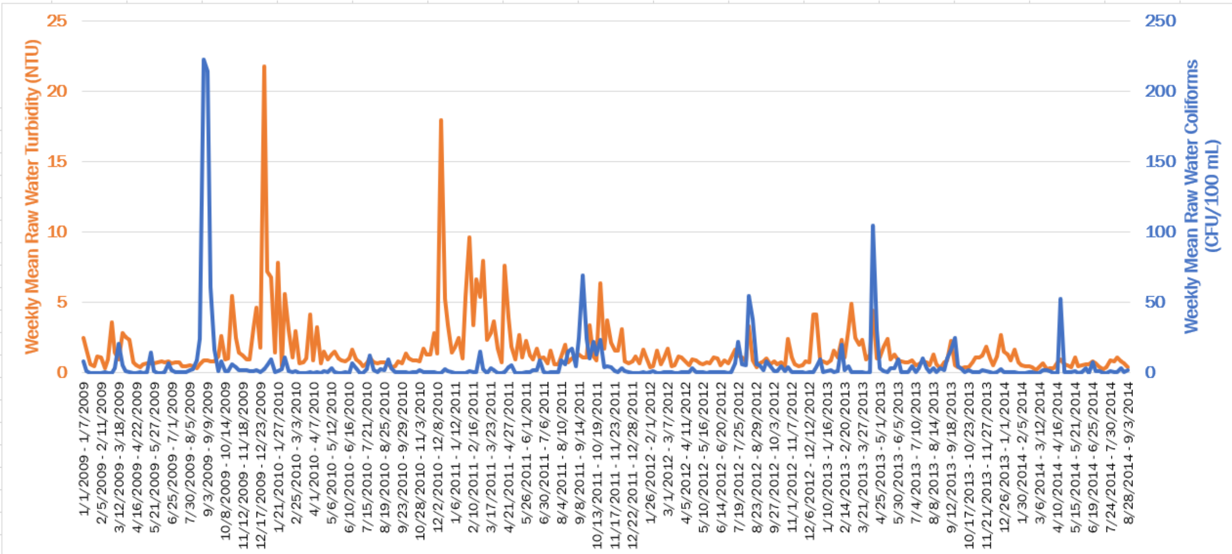

Figure 6-34: Milwaukee, Wisconsin Linnwood raw water turbidity and total coliforms.

6.5.5 Toronto, Ontario

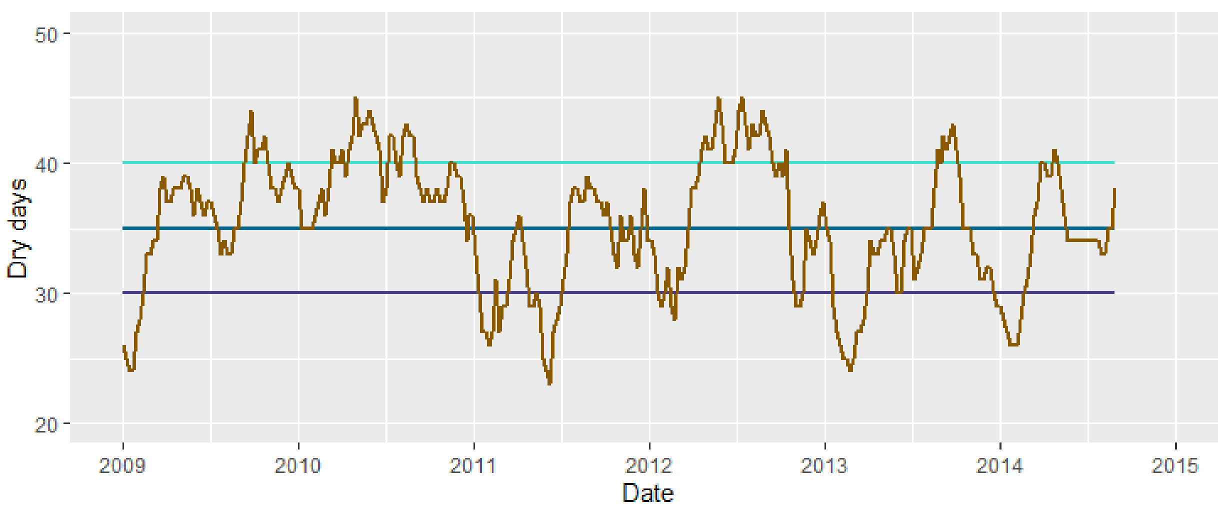

Figure 6-35: Toronto, Ontario weekly time series of the number of dry days in the preceding 60 days, January 1, 2009 through August 31, 2014 (296 weeks). The purple line indicates the 30-day threshold. The blue line indicates the 35-day threshold. The turquoise line represents the 40-day threshold. Points above the lines were classified as dry periods and points below the lines were classified as wet periods. See Table 6-7 for number and proportions for each dry/wet threshold.

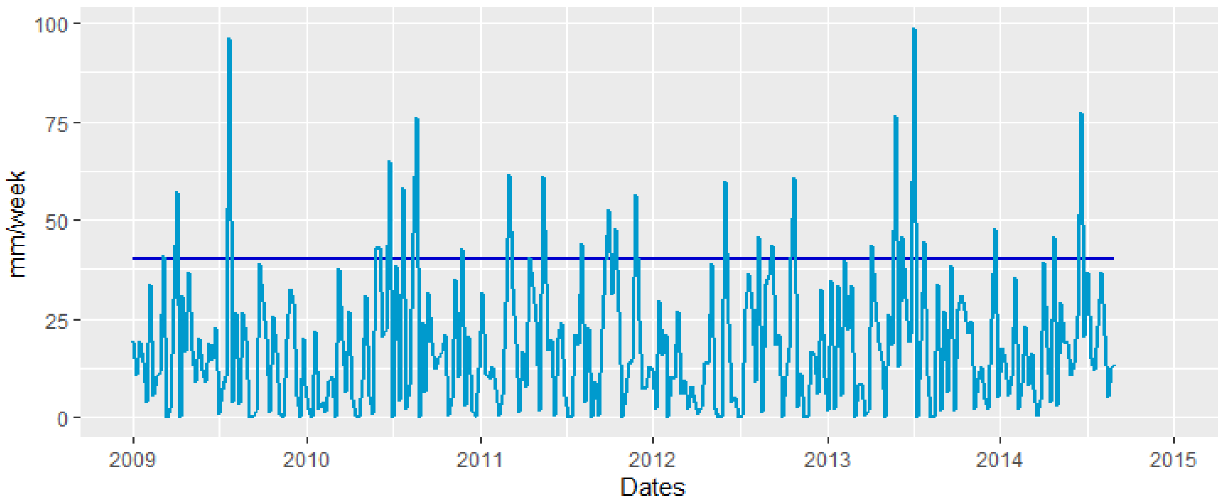

Figure 6-36: Toronto, Ontario weekly time series of precipitation. Purple line indicates the weekly cumulative precipitation 90th percentile of 40.2 mm. Points above the purple line were classified as extreme precipitation weeks.

Table 6-11: Toronto, Ontario extreme precipitation weeks. An extreme precipitation week had precipitation that exceeded the 90th percentile for the study period. For Toronto, the 90th percentile for cumulative weekly precipitation was 40.2 mm. There were 30 extreme event weeks (formula included zero values in the dataset).

90th percentile precipitation weeks		
2009-03-05 - 2009-03-11	2011-03-03 - 2011-03-09	2013-04-04 - 2013-04-10
2009-04-02 - 2009-04-08	2011-04-14 - 2011-04-20	2013-05-23 - 2013-05-29
2009-07-23 - 2009-07-29	2011-05-12 - 2011-05-18	2013-06-06 - 2013-06-12
2010-05-27 - 2010-06-02	2011-08-04 - 2011-08-10	2013-07-04 - 2013-07-10
2010-06-03 - 2010-06-09	2011-09-29 - 2011-10-05	2013-07-25 - 2013-07-31
2010-06-24 - 2010-06-30	2011-10-13 - 2011-10-19	2013-12-19 - 2013-12-25
2010-07-22 - 2010-07-28	2011-11-24 - 2011-11-30	2014-04-24 - 2014-04-30
2010-08-12 - 2010-08-18	2012-05-31 - 2012-06-06	2014-06-19 - 2014-06-25
2010-08-19 - 2010-08-25	2012-08-09 - 2012-08-15	
2010-11-25 - 2010-12-01	2012-09-06 - 2012-09-12	
	2012-10-18 - 2012-10-24	
	2012-10-25 - 2012-10-31	

Based on a precipitation pattern definition of 35 days of no precipitation in the preceding 60 days as dry (Table 6-7 and Figure 6-35), the font color indicates if the extreme precipitation event occurred during a wet precipitation pattern (n=15) or dry precipitation pattern (e.g., abrupt precipitation spike) (n=15).

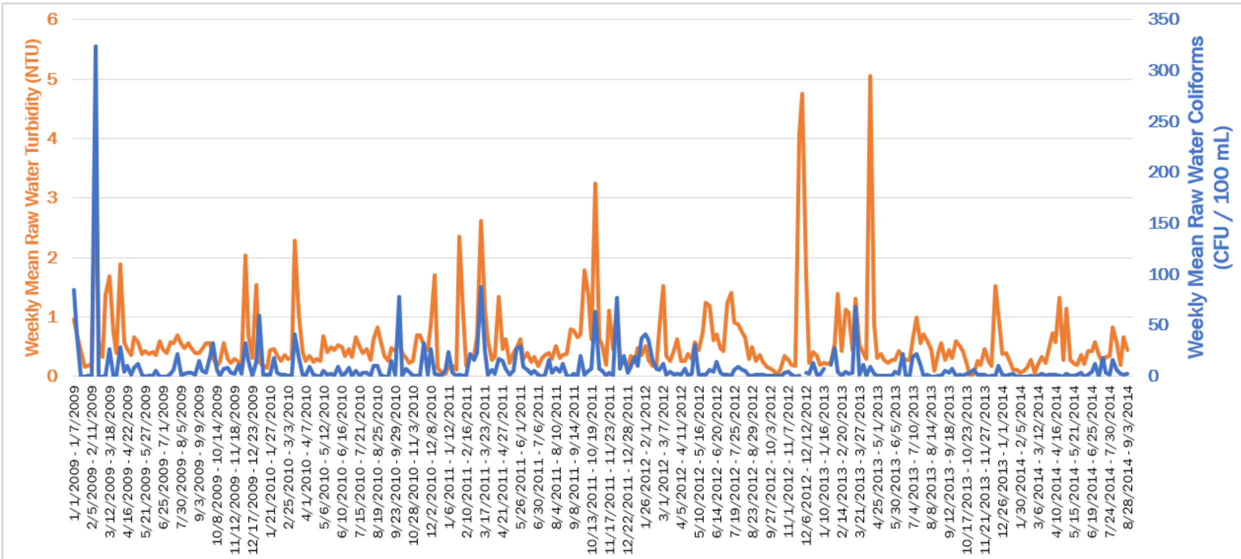

Figure 6-37: Toronto, Ontario Clark raw water turbidity and total coliforms.

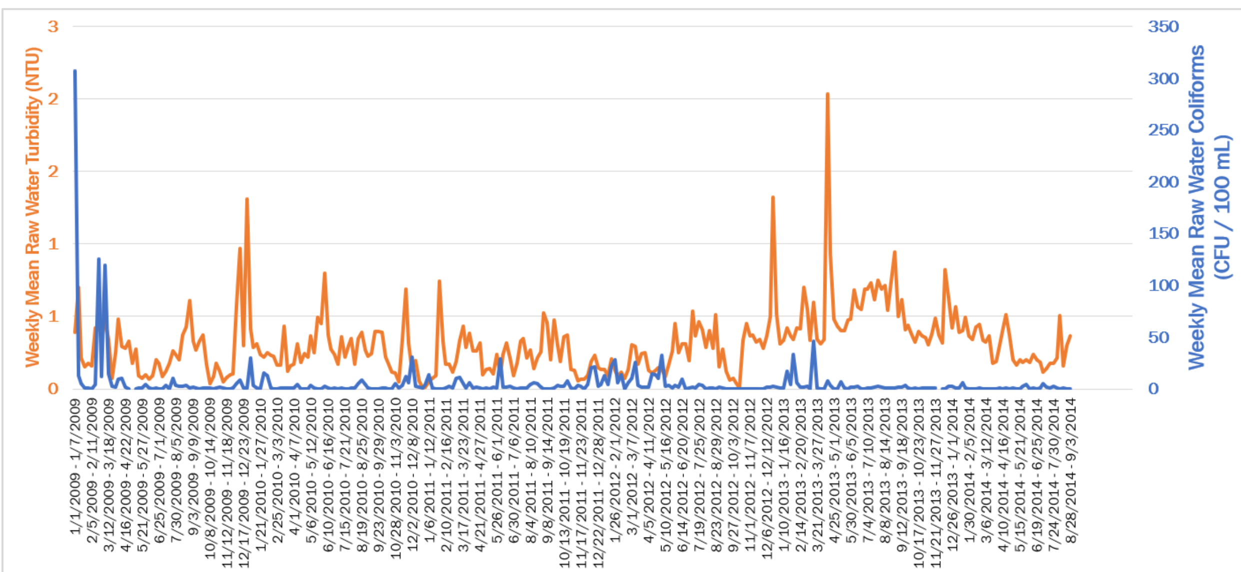

Figure 6-38: Toronto, Ontario Harris raw water turbidity and total coliforms.

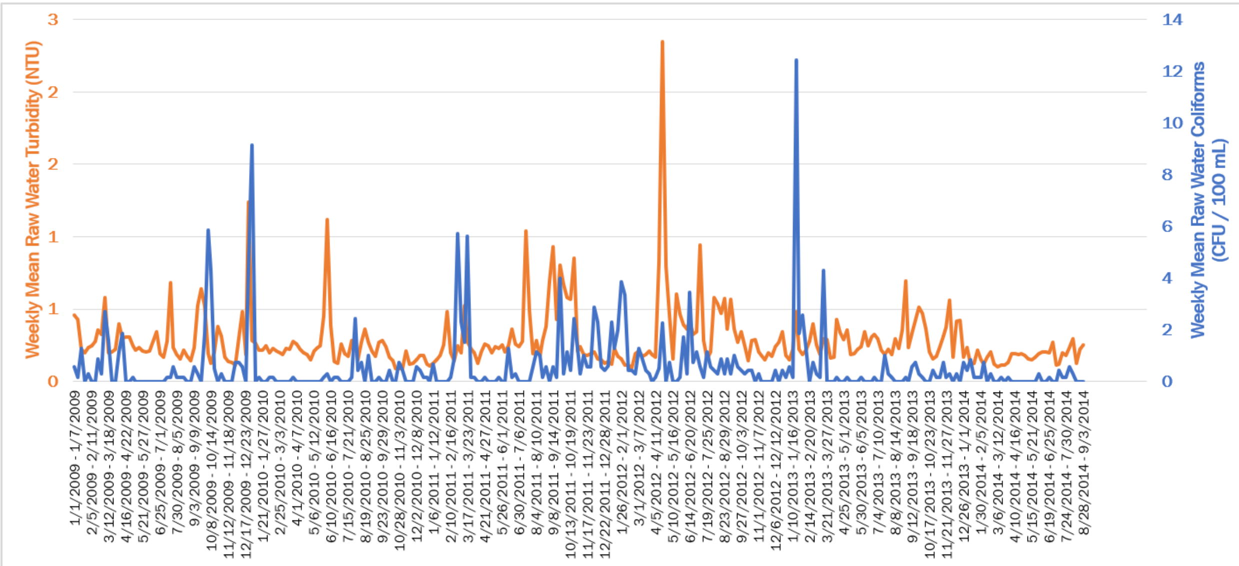

Figure 6-39: Toronto, Ontario Horgan raw water turbidity and total coliforms.

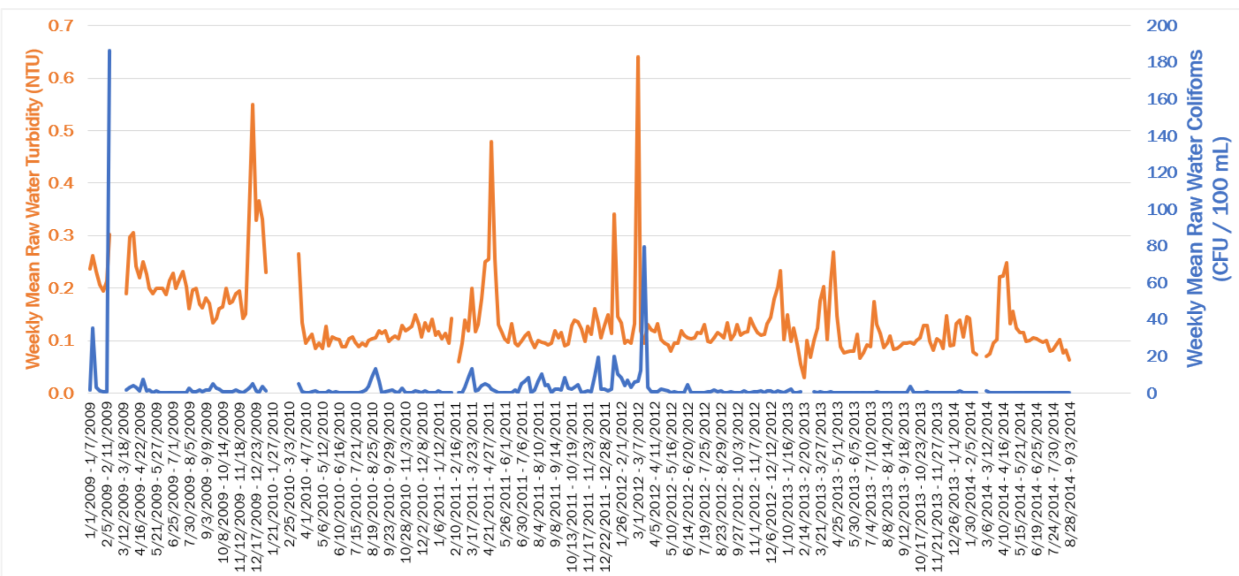

Figure 6-40: Toronto, Ontario Island raw water turbidity and total coliforms.

6.6 Statistical model terms and fit

To determine which indicators produced the best statistical model to use for the population attributable risk analyses, the weather, raw water quality, and lake current indicators for each city's intake were methodically added to the distributed lag nonlinear regression models and tested using the qAIC goodness-of-fit score for each model. These indicators included the cumulative weekly AGI cases (cryptosporidiosis and giardiasis), precipitation pattern (wet or dry), turbidity, total coliforms and lake current speed and direction from all the raw water intakes.

Lake current data were obtained through the Great Lakes Observing System for the National Oceanic and Atmospheric Administration Great Lakes Coastal Forecasting System[6] via a website query and personal communication with researchers at the National Oceanic and Atmospheric Administration Great Lakes Environmental Research Laboratory. The Great Lakes Coastal Forecasting System is a numerical model that calculates waves, currents, and temperatures for each of the Great Lakes. The Great Lakes Coastal Forecasting System Nowcast model provides estimates of lake conditions near the point query in three-hour intervals. Data for the model are collected in cooperation with various agencies, such as Environment and Climate Change Canada, for locations along Lake Ontario.[7] Lake currents velocity at all depths modeled were obtained near the raw water intakes for each city. Daily lake current velocities were aggregated to rolling seven-day mean speed and direction values. The weekly mean direction component was used to determine if currents were onshore or offshore for each data week.

Both raw water indicators (turbidity and total coliforms) are the mean weekly values.

The 296-week study period was from January 1, 2009 through August 31, 2014.

As an example, see the R code used to analyze Green Bay in **Appendix 6.7**.

6.6.1 Model terms and qAIC results

All models include a Fourier term to adjust for seasonality, a spline term to adjust for trend and a holiday factor to adjust for weeks when a holiday may have affected healthcare service or reporting.

Model 1 includes AGI cases and precipitation pattern but not any water intake data.

Model 2 includes the AGI cases, precipitation pattern, cumulative weekly precipitation and turbidity data.

---

[6] More information available at: glerl.noaa.gov/res/glcfs/.

[7] Chu, P.Y., Kelley, J.G.W., Mott, G.V., Zhang, A., Lang, G.A., 2011. Development, implementation, and skill assessment of the NOAA/NOS Great Lakes Operational Forecast System. Ocean Dyn. 61, 1305–1316. DOI: 10.1007/s10236-011-0424-5.

Model 3 includes the AGI cases, precipitation pattern, cumulative weekly precipitation, turbidity and total coliforms data.

Model 4 (surface) includes the AGI cases, precipitation pattern, cumulative weekly precipitation, turbidity, total coliforms data, onshore/offshore factor (based on current direction at the surface) and lake current surface direction (Great Lakes Observing System).

Model 4 (depth) includes the AGI cases, precipitation pattern, cumulative weekly precipitation, turbidity, total coliforms data, and onshore/offshore factor (based on current direction at depth nearest to intake crib or deepest depth).

Model 5 (surface) includes the AGI cases, precipitation pattern, cumulative weekly precipitation, turbidity, total coliforms data, onshore/offshore factor (based on current direction at the surface), lake current surface direction and lake current surface speed.

Table 6-12 displays the qAIC goodness-of-fit results for each model tested. Based on these results, the best model was determined to be Model 3, which was used for our population attributable risk analyses.

Table 6-12: Model fit for each raw water intake. Font color indicates if the model fit improved (green – qAIC decreased) from the previous model or if the model fit declined (red – qAIC increased) from the previous model. The 4-surface and 4-depth models were compared against model 3.

City	Intake	Model	qAIC	City	Intake	Model	qAIC
Green Bay	Kewaunee	1	605	Toronto	Clark	1	1540
		2	576			2	1514
		3	572			3	1425
		4-surface	583			4-surface	1505
		4-depth	574			4-depth	1475
		5-surface	724			5-surface	1525
Hamilton	Hamilton	1	818		Harris	1	1540
		2	795			2	1516
		3	787			3	1417
		4-surface	801			4-surface	1453
		4-depth	790			4-depth	1425
		5-surface	816			5-surface	1475
Milwaukee	Howard	1	1210		Horgan	1	1540
		2	1118			2	1483
		3	1140			3	1486
		4-surface	1165			4-surface	1509
		4-depth	1142			4-depth	1486
		5-surface	1185			5-surface	1538
	Linnwood	1	1210		Island	1	1540
		2	1206			2	1267
		3	1210			3	1227
		4-surface	1219			4-surface	1262
		4-depth	1212			4-depth	1229
		5-surface	1244			5-surface	1278

6.7 R Code for Green Bay, Wisconsin data

This appendix shows the R code used to conduct the distributed lag nonlinear regression models (DLNM) analyses and produce the relative risk figure for the Green Bay, Wisconsin dataset.

```
###R code using DLNM package for Green Bay's data###

# This code was written by Ryan Graydon (2018-2020 IJC Sea Grant Fellow) to reproduce
    Figure 2 in Chhetri et al. (2017): relative risk (90th percentile precipitation) after a dry
    period

  # For any questions about the code, contact Ryan Graydon (rgraydon.ijc@gmail.com) and
    Jennifer Boehme (jennifer.boehme@ijc.org) at the International Joint Commission's
    Great Lakes Regional Office


# Ascertain and set your working directory, which is where any exported files will be saved

getwd() # shows what your current working directory is

setwd("path")


rm(list = ls())  # Remove all data from the environment

remove() # If necessary, use function to remove (and then rewrite) data from the environment


# Open packages for use

library(readxl);library(tidyverse);library(lubridate);library(tseries);

library(tsModel);library(splines);library(dlnm);library(aod)

    # If a package isn't currently installed, use the install.packages("packagename") function
    to download each package


# Help files, if needed

vignette("dlnmOverview");vignette("dlnmTS");vignette("dlnmExtended");vignette("dlnmPenaliz
    ed")
```

```
qaic <- function(model) {
  phi <- summary(model)$dispersion
  loglik <- sum( dpois( model$y, model$fitted.values, log=TRUE) )
  return(-2*loglik + 2*summary(model)$df[3]*phi)
} # analyzes model fit; lower number indicates a better fit


# Green Bay
GreenBay <- read_xlsx("GreenBay_DLNM_Data_2020-04-10.xlsx", sheet="ZIP_Dates
        Adjusted")
{GreenBay$Dates <- as.Date(GreenBay$Dates, tryFormats = "%m/%d/%Y")
    GreenBay$Year <- as.factor(GreenBay$Year)
    GreenBay$Season <- as.factor(GreenBay$Season)
    GreenBay$Month <- month(GreenBay$Dates,label=T,abbr=T)
    GreenBay$GLERLOnOff <- as.factor(GreenBay$GLERL_OnOff_10m) # On means the
        modelled lake current at 10 meters depth was towards the shore
    GreenBay$GLOSOnOff <- as.factor(GreenBay$GLOS_OnOff_0m) # On means the
        modelled lake current at the surface was towards the shore
    GreenBay$Pattern30 <- as.factor(GreenBay$Pattern30) # Wet or Dry precipitation pattern
        <=30 days in the preceding 60 days
    GreenBay$Pattern35 <- as.factor(GreenBay$Pattern35) # Wet or Dry precipitation pattern
        <=35 days in the preceding 60 days
    GreenBay$Pattern40 <- as.factor(GreenBay$Pattern40) # Wet or Dry precipitation pattern
        <=40 days in the preceding 60 days
    GreenBay$Holiday <- as.factor(GreenBay$Holiday) # Holiday closures of healthcare
        facilities
    GreenBay$Precip90th <- as.factor(GreenBay$Precip90th)} # Yes means week was >=90th
        percentile weekly cumulative precipitation
glimpse(GreenBay)
```

```
summary(GreenBay)

GBfourier <- harmonic(GreenBay$DataWeek,nfreq=2,period=52) # second degree fourier terms

GBspl <- ns(GreenBay$DataWeek,df=15) # ns is the natural cubic spline function

GBmodel1 <- glm(TotalCases~GBfourier+factor(Holiday)+factor(Pattern40)+GBspl,
        family=quasipoisson,data=GreenBay);summary(GBmodel1)

qaic(GBmodel1) # AIC 605

acf(residuals(GBmodel1),lag.max=104) # lag.max may need to be adjusted to our dataset

anova(GBmodel1,test="LRT")

wald.test(b = coef(GBmodel1), Sigma = vcov(GBmodel1), Terms = 2:5)

lagknots<-logknots(6,3);lagknots

GBns.precip<- crossbasis(GreenBay$Precip,lag=8,
        argvar=list(fun="thr",thr.value=25),arglag=list(fun="ns",knots=lagknots)) # adds
        precipitation to the model

GBns.NTU<- crossbasis(GreenBay$RwTurbidityMean,lag=8,
        argvar=list(fun="ns",df=3,cen=0),arglag=list(fun="ns",knots=lagknots));summary(GBns.
        NTU) # adds total turbidity to the model

GBns.CFU<-
        crossbasis(GreenBay$RwColisMean,lag=8,argvar=list(fun="thr",thr.value=0.25),arglag=
        list(fun="ns",knots=lagknots));summary(GBns.CFU) # adds total coliforms to the model

GBns.LCD<-
        crossbasis(GreenBay$GLOS_LakeCrtDir,lag=8,argvar=list(fun="ns",df=3,cen=0),arglag
        =list(fun="ns",knots=lagknots));summary(GBns.LCD) # adds lake current direction at
        the surface to the model

GBns.LCS<- crossbasis(GreenBay$GLOS_LakeCrtSpd,lag=8,
        argvar=list(fun="ns",df=3,cen=0),arglag=list(fun="ns",knots=lagknots));summary(GBns.
        LCS) # adds lake current speed at the surface to the model
```

```
summary(GBns.precip);summary(GBns.NTU);summary(GBns.CFU)

GBmodel2 <-
    glm(TotalCases~GBns.precip+GBns.NTU+GBfourier+factor(Holiday)+factor(Pattern40)
    +GBspl,family=quasipoisson,data=GreenBay);summary(GBmodel2) # AIC NA

qaic(GBmodel2) # AIC 576, improved from 605

acf(residuals(GBmodel2),lag.max=104)

GBmodel3 <-
    glm(TotalCases~GBns.precip+GBns.NTU+GBns.CFU+GBfourier+factor(Pattern40)+fac
    tor(Holiday)+GBspl,family=quasipoisson,data=GreenBay);summary(GBmodel3) # AIC
    NA

qaic(GBmodel3) # AIC 572, improved from 576 (GBmodel2) and 605 (GBmodel1)

acf(residuals(GBmodel3),lag.max=104)

GBmodel4 <-
    glm(TotalCases~GBns.precip+GBns.NTU+GBns.CFU+GBfourier+GBns.LCD+factor(G
    LOSOnOff)+factor(Pattern40)+factor(Holiday)+GBspl,family=quasipoisson,data=Green
    Bay);summary(GBmodel4) # AIC NA

qaic(GBmodel4) # AIC 583, declined from 572 (GBmodel3) and from 576 (GBmodel2) but
    improved from 605 (GBmodel1)

acf(residuals(GBmodel4),lag.max=104)

GBmodel4_GLERL <-
    glm(TotalCases~GBns.precip+GBns.NTU+GBns.CFU+GBfourier+factor(GLERLOnOff
    )+factor(Holiday)+factor(Pattern40)+GBspl,family=quasipoisson,data=GreenBay);summ
    ary(GBmodel4_GLERL) # AIC NA

qaic(GBmodel4_GLERL) # AIC 574, declined from 572 (GBmodel3) and from 576 (GBmodel2)
    but improved from 605 (GBmodel1)
```

```
GBmodel5 <-
    glm(TotalCases~GBns.precip+GBns.NTU+GBns.CFU+GBfourier+GBns.LCD+GBns.L
    CS+factor(GLOSOnOff)+factor(Holiday)+factor(Pattern40)+GBspl,family=quasipoisson
    ,data=GreenBay);summary(GBmodel5) # AIC NA

qaic(GBmodel5) # AIC 724, declined from 583 (GBmodel4), from 572 (GBmodel3), from 576
    (GBmodel2) and from 605 (GBmodel1)

acf(residuals(GBmodel5),lag.max=104)


GBns.pred <- crosspred(GBns.precip,GBmodel3,cumul=T,lag=8);summary(GBns.pred)


##RR Plot##

plot(GBns.pred,var=60,type="p",ci="bars",col=1,pch=19,

    main="Green Bay: Relative Risk Prediction Model\nExtreme Precipitation Preceded by
    Dry Pattern\nwith Raw Water Turbidity & Total Coliforms",

    ylim=c(0.25,2),xlab="Lag (weeks)",ylab="Relative risk (90th percentile precipitation)")

#export dimensions 620 x 400


#################################################################
```